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(MANTECH) PROGRAM

ULTRASONICALLY ASSISTED MACHINING OF AIRCRAFT PARTS

JANET DEVINE and PHILIP C. KRAUSE
Sonobond Corporation
200 East Rosedale Avenue
West Chester, Pennsylvania 19380

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A tool post for ultrasonic activation of cutting tools on a turret lathe was designed, fabricated and given preliminary evaluation on a LeBlond engine lathe, turning difficult-to-machine wrought metal alloys, including ESR 4340 steel, 4340 steel, 9310 steel, 17-4 PH steel, several titanium alloys and Refractaloy 26. With the ultrasonic assist, metal removal rates were increased by factors up to 730 percent, tool wear and tool breakage were

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) reduced and tool chatter was eliminated. Ultrasonically cut chips had a larger curl radius, lower hardness and less heat discoloration than conventionally cut chips. It was recommended that the ultrasonic tool post be refined and installed on a turret lathe for evaluation in a production environment.

PREFACE

This report on ultrasonically assisted machining of aircraft parts was prepared by Sonobond Corporation, West Chester, PA, under Army Contract DAAG46-78-C-0059. This project was accomplished as part of the U.S. Army Aviation Research and Development Command Manufacturing Technology program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques and equipment for use in the production of Army materiel. Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments should be sent to: U.S. Army Aviation Research and Development Command, ATTN: DRDAV-EGX, 4300 Goodfellow Boulevard, St. Louis, MO 63120.

Mr. Arthur Ayvazian of the Army Materials and Mechanics Research Center, DRXMR-AP, Watertown, MA, served as Contracting Officer's Representative on this project. The work performed at Sonobond was under the technical supervision of Mrs. Janet Devine and Philip C. Krause served as administrative supervisor.

Assistance in the program was provided by Hughes Helicopters, Division of Summa Corporation, Culver City, CA, with Kenneth Niji providing technical liason.

This report covers Phase I of an ongoing program in ultrasonic machining.

The findings of this report are not to be construed as an official Department of the Army position.

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I. INTRODUCTION

This program was undertaken to evaluate the technological and economic benefits achievable with ultrasonic energy application during lathe cutting of difficult-to-machine materials and to define requirements for ultrasonically processing such materials on a production basis.

Laboratory investigations during the last 20 years have demonstrated significant benefits with ultrasonic machining in terms of increased rates of material removal, decreased cutting forces, reduced tool wear, elimination of tool chatter and altered surface finish. Most of this work involved the more readily machinable materials such as aluminum, carbon steel, austenitic stainless steel and the like. Low-power (up to 600 watts) prototype ultrasonic systems were developed and successfully used for such applications.

The current work has extended the technology to materials that present machinability problems, particularly those used in the fabrication of Army aircraft such as the YAH-64. It involved the development of a high power (4000-watts) ultrasonic machining system for installation on a turret lathe and preliminary evaluation with several high-strength materials designated by the Army.

A. BACKGROUND

Many aircraft parts are made of metal alloys that are difficult to machine by conventional methods. Materials such as 6Al-4V titanium alloy, hardened 17-4 PH stainless steel and hardened 4340 and 9130 steel alloys have valuable properties such as high strength, high hardness and good fatigue resistance, but high cutting forces are usually required and material removal rates are low. Turning operations for these materials are slow and costly. In addition, such materials tend to stick to the cutting tools and edge build-up on the tool frequently produces an undesirable surface finish.

Typical problems are encountered, for example, in the machining of large helicopter rotor head parts such as the following:

1. With parts made of 6Al-4V titanium alloy, the turning speed must be slow enough so that a tool required to maintain satisfactory surface finish will not need to be changed during the final continuous cut.

2. Thread milling at slow removal rates is required for external thread cutting of hardened 4130 and 4340 steel

alloys. Poor surface finish is obtained with the more rapid lathe cutting of such threads.

3. In straight OD turning, hardened 4130 steel requires low machining rates to avoid tearing of the surface.

Unusually difficult problems are encountered in the machining of the electroslag refined steels such as ESR 4340, which is used in drive control, flight control and hydraulic systems. Because of the necessity for grinding to final surface finish, the turning costs may be tripled or quadrupled over the costs for the more common steel alloys (Ref. 1). The fixturing must be more rigid because of the toughness of the material and the turning feeds and speeds are slower. A typical material removal rate is 0.005 inch per pass to obtain the desired surface finish. Tool wear is rapid and tool breakage is frequent. Extreme care is required to prevent overheating of the material.

Such materials and operations are prime candidates for improvement and ultrasonically assisted turning offers one avenue for such improvement.

B. ULTRASONICALLY ASSISTED MACHINING

The effectiveness of ultrasonic energy applied during lathe turning has been demonstrated in a number of investigations carried out in the United States and elsewhere. The major studies are summarized in Appendix A.

One of the prime effects is a significant increase in material removal rate, as illustrated in Figure 1 for 2024-T3 aluminum alloy and in Figure 2 for 1018 carbon steel. These show a consistent pattern of increased cutting rate (up to fourfold) as the ultrasonic power level is increased without increasing the cutting torque.

Figure 3 shows the reduction in forces on the cutting tool with ultrasonic activation for these same materials over a range of material removal rates. Again the force reduction becomes greater as the ultrasonic power is increased. With such reduced forces, extended tool life can be anticipated.

The surface finishes obtained with ultrasonic and non-ultrasonic turning are shown in Figures 4 and 5. On the aluminum, the ultrasonic turned sections are characterized by a matte surface, while those non-ultrasonically turned are super-

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(1) R. York, Bertea Corporation, Irvine, CA, Private Communication to Hughes Helicopters, Culver City, CA, June 27, 1974.

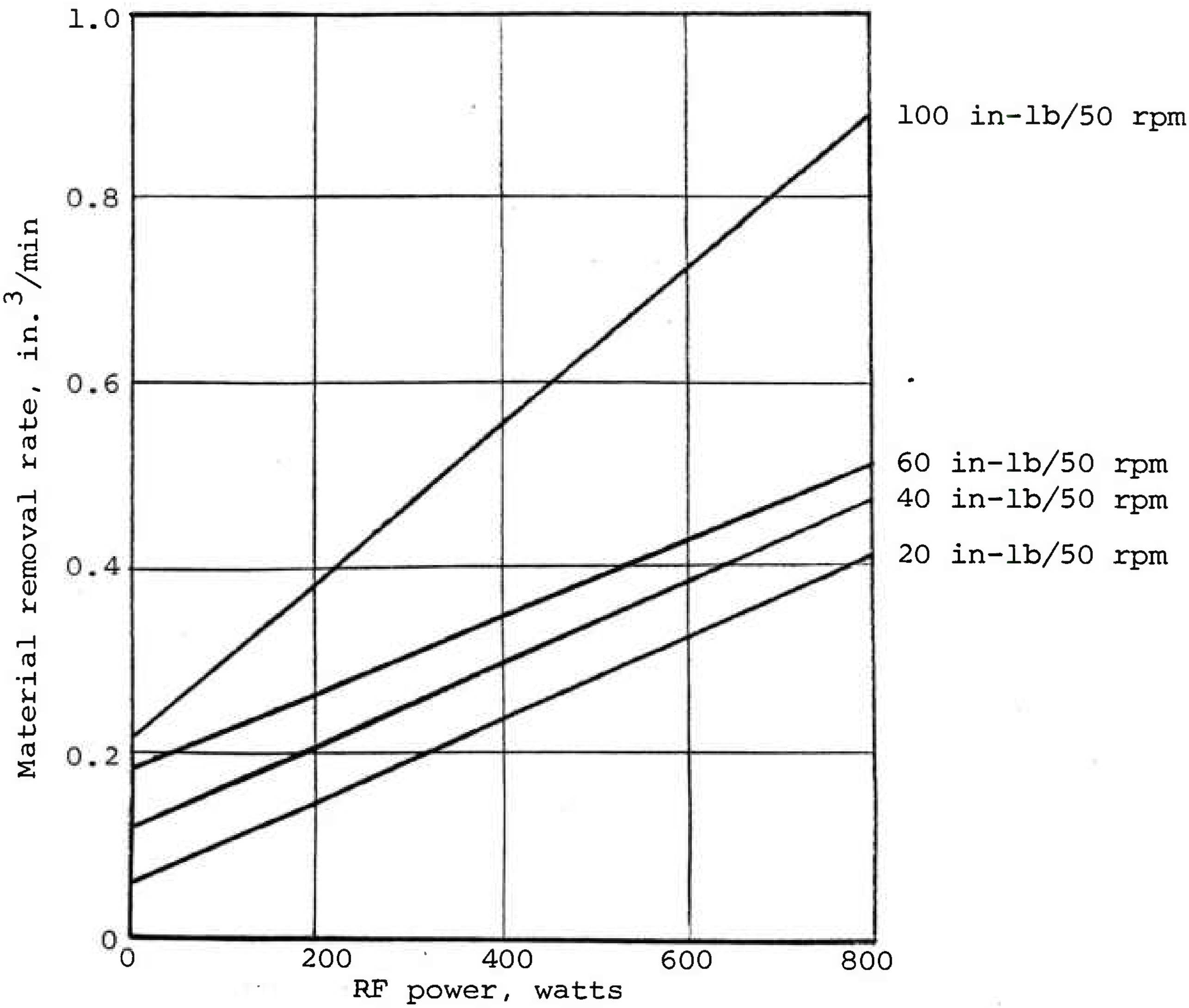


Figure 1. Material removal rate as a function of ultrasonic power while machining 2024-T6 aluminum alloy.

Initial diameter: 3.52 inches
Feed rate: 0.008 inch per revolution
Parameters: Driving torque/rpm

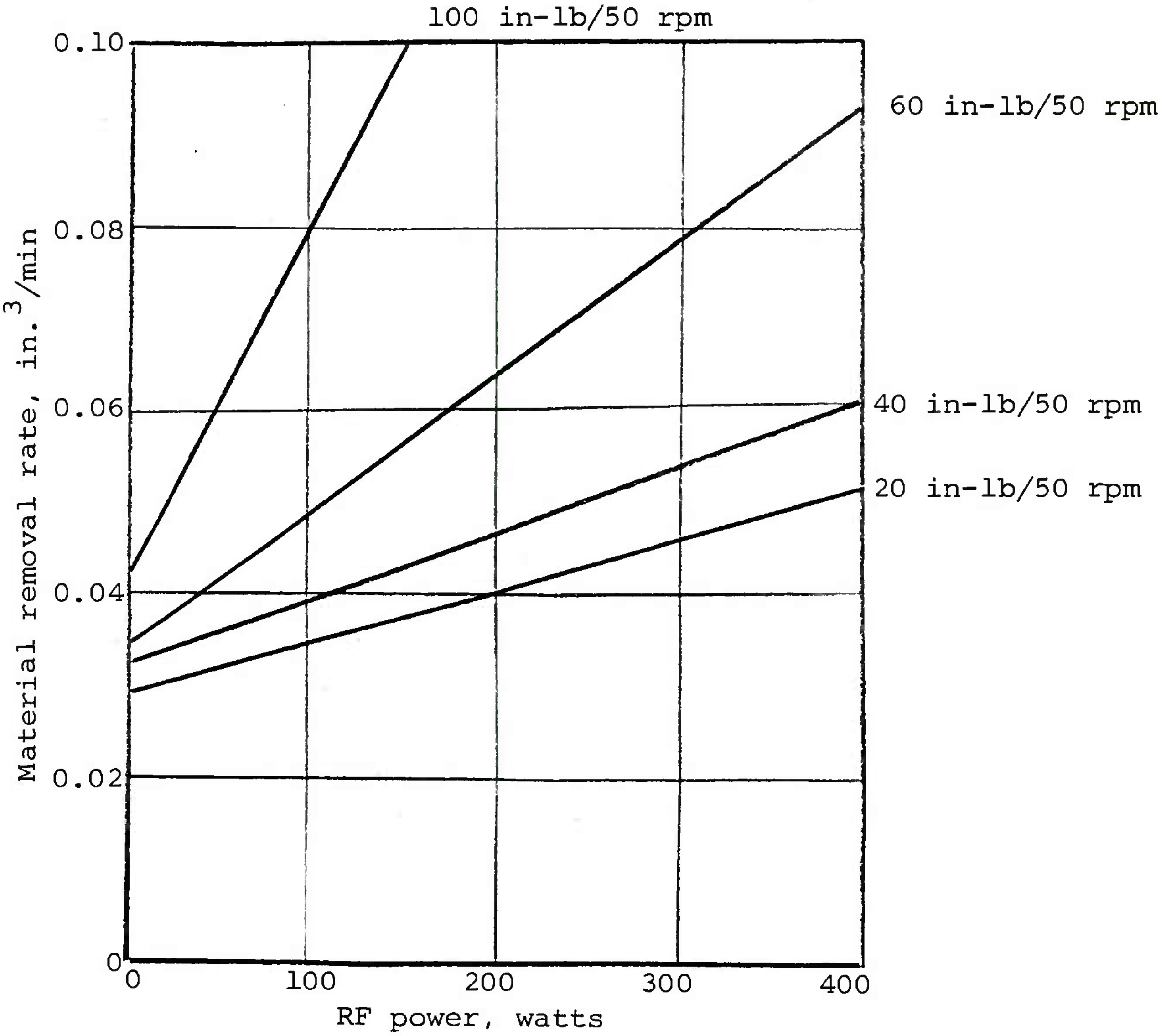


Figure 2. Material removal rate as a function of ultrasonic power while machining 1018 HR carbon steel.

Initial diameter: 3.52 inches
Feed rate: 0.0008 inch per revolution
Parameters: Driving torque/rpm

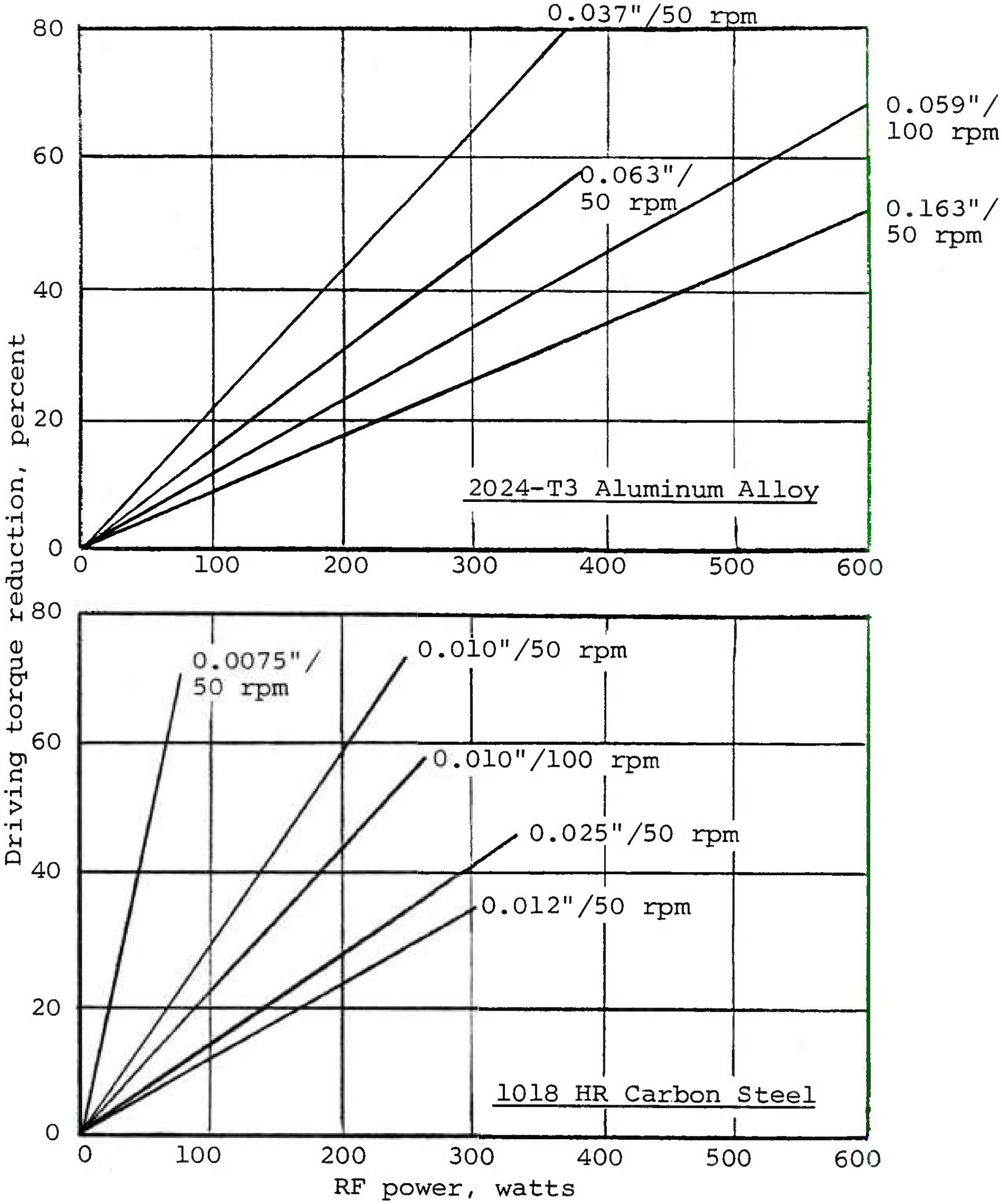
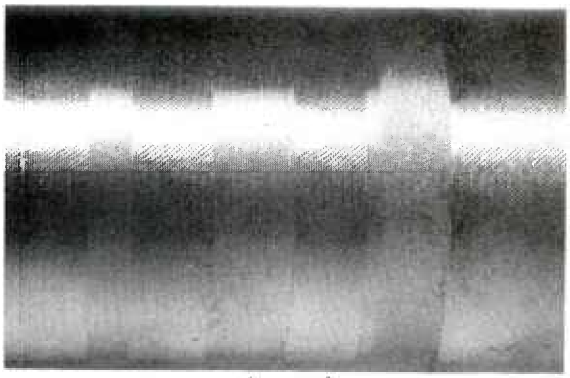


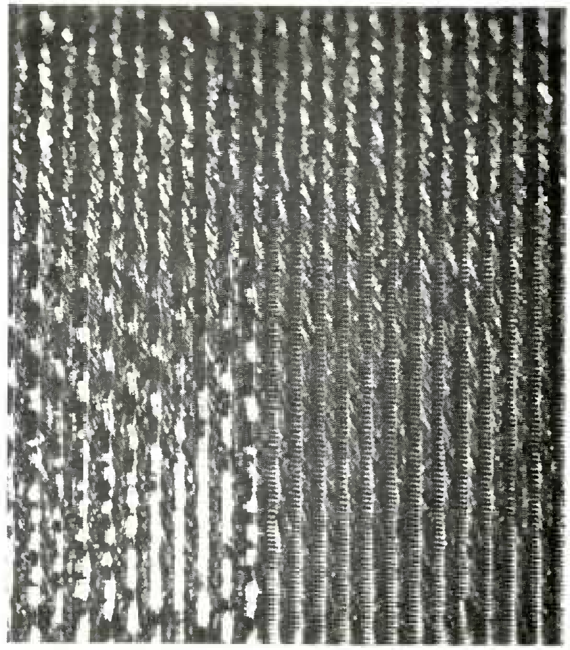
Figure 3. Cutting force reduction obtained with ultrasonic activation of cutting tool during lathe turning.

Initial diameter: 3.52 inches
Feed rate: 0.008 inch per revolution
Parameters: Cut depth/rpm
(1 rpm ≈ 1 SFM)



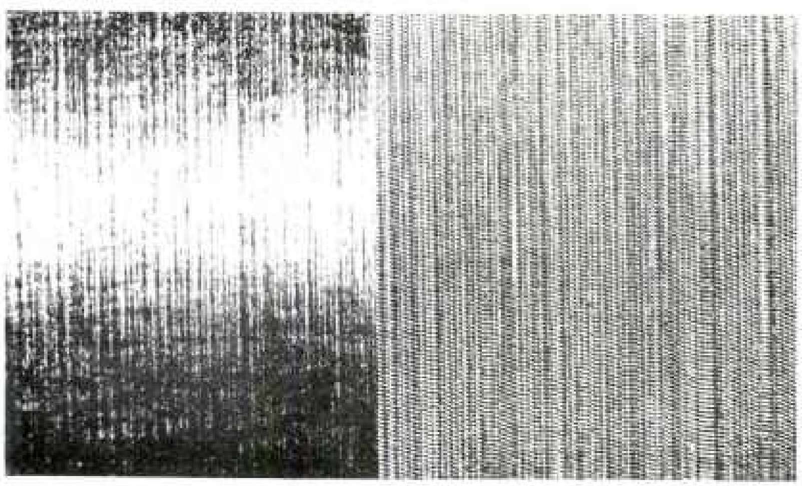
Ultrasonic

Non-ultrasonic



Non-ultrasonic (10X) Ultrasonic

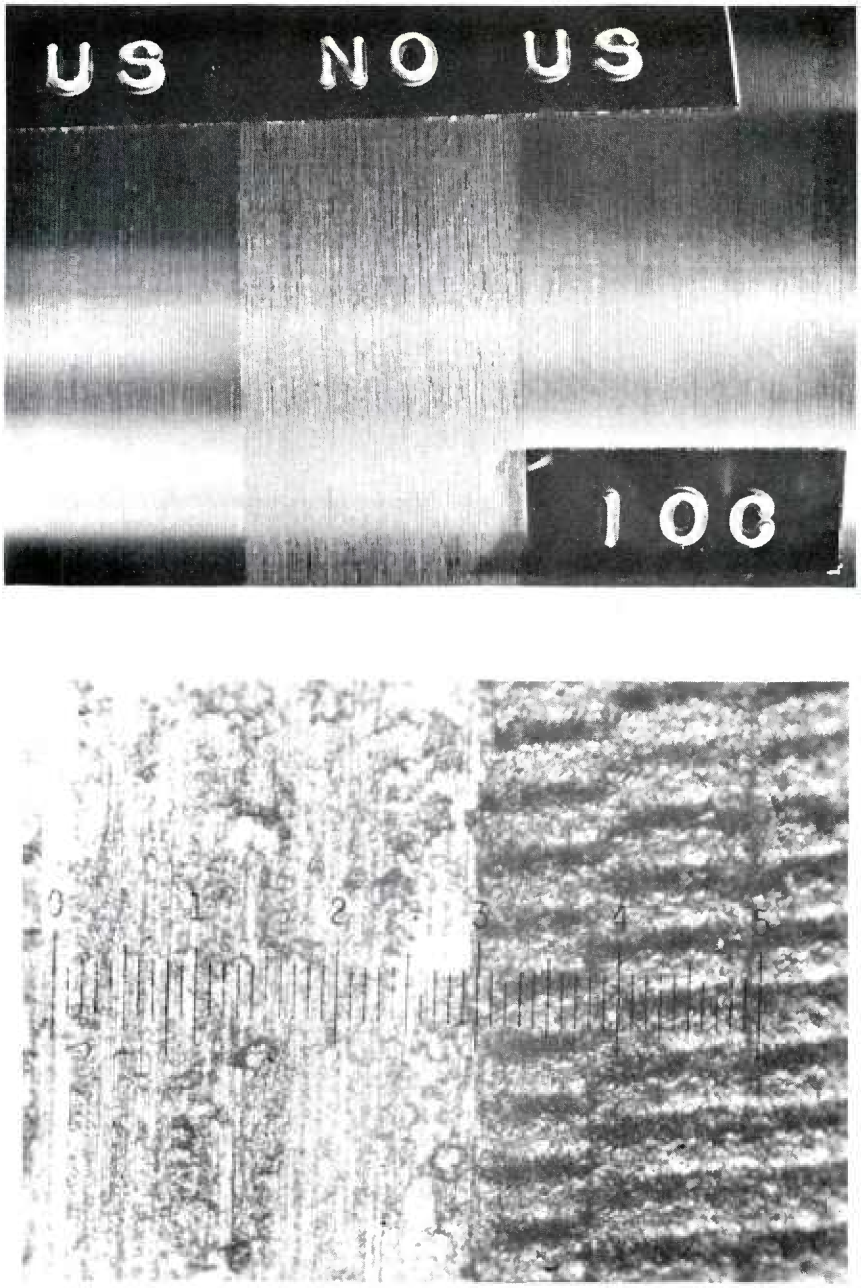
Coarse Turned



Non-ultrasonic Ultrasonic

Fine Turned (2X)

Figure 4. Aluminum surface finishes obtained with ultrasonic and non-ultrasonic turning.



Non-ultrasonic Ultrasonic
(125X)

Figure 5. Surface finishes obtained with ultrascnic and non-ultrasonic turning of 1018 steel.

ficially shiny. In the high-magnification photographs, there appears to be less gouging and tearing of the surface with the ultrasonic assist. The minute striations of uniform regularity reflect the ultrasonic vibration cycles. Their spacing depends on the vibratory frequency in relation to the cutting speed.

The striation effect is even more pronounced on the 1018 carbon steel (Figure 5). The non-ultrasonically turned section shows considerable gouging and tearing of the material.

Etched cross sections of the turned material are shown in Figure 6. Again the irregular gouging of the surface with conventional turning is apparent. By comparison, the ultrasonically turned surface is relatively smooth and there is little or no evidence of subsurface workhardening.

Visual and microscopic examination of chips obtained during machining of these materials (Figure 7) revealed, for the non-ultrasonically cut chips:

1. A tight, small-radius curl.

2. A rough chip edge on the cut side, showing "tear-away" trails, indicating non-smooth cutting.

3. A generally shiny outer surface with evidence of burnishing, resulting either from the mode of cutting and tearing from the surface or from drag on the tool surface.

4. Erratic lateral flow and torn surfaces.

On the other hand, the ultrasonically cut chips were characterized by:

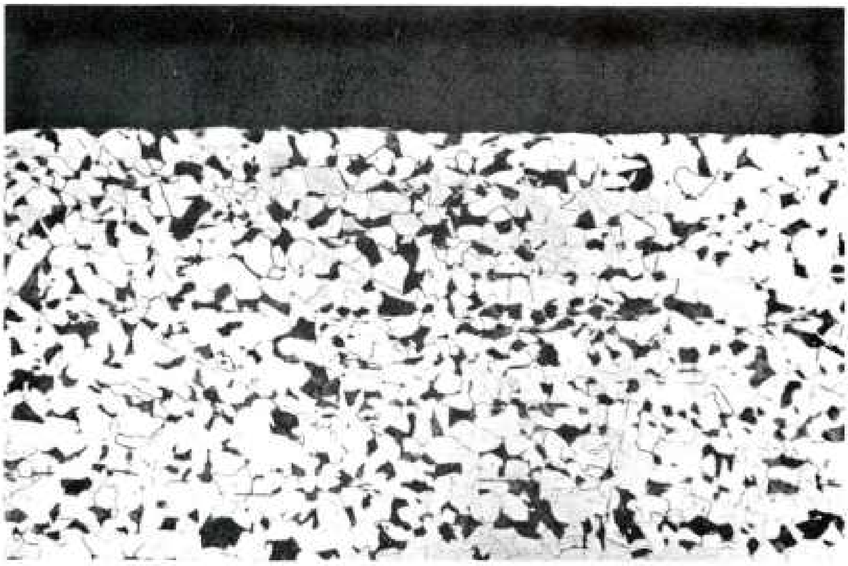
1. A significantly greater radius for the curl.

2. A chip edge that was generally smooth, with evidence of a continuous cut and no indication of "tear-away."

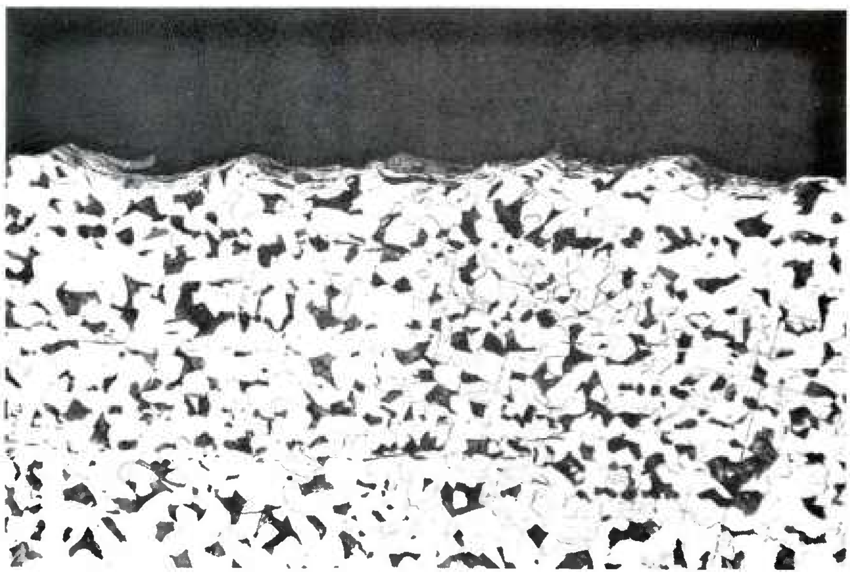
3. Outer curl surfaces of a matte finish, indicating relatively clean cutting and minimal drag along the upper surface of the tool.

4. Uniform lateral flow; both chip thickness and width were less than for non-ultrasonic chips.

A further observation during machining of these materials was the elimination of chatter. Under conditions that produced chatter with conventional machining, the chatter immediately

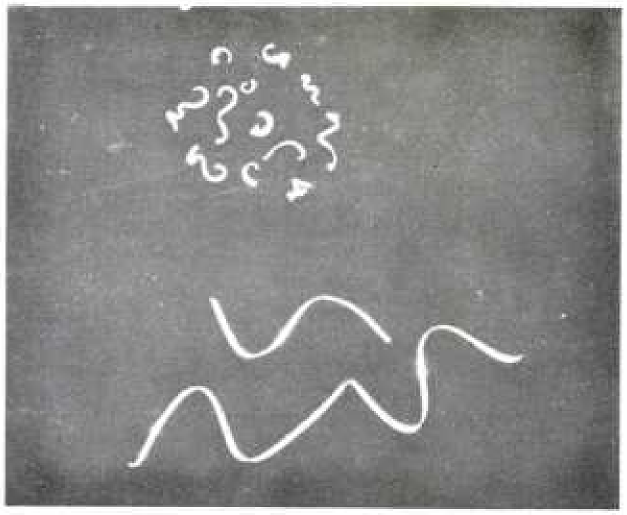


Ultrasonic



Non-Ultrasonic

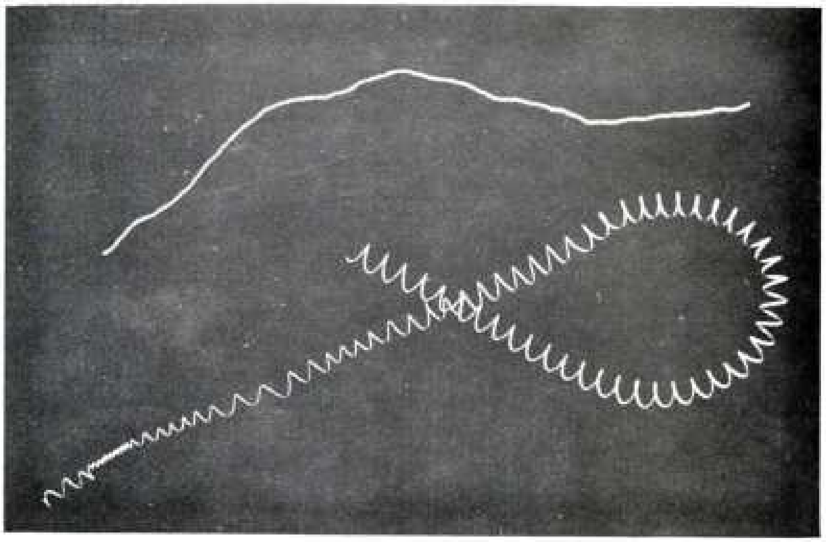
Figure 6. Sections showing surface profiles of machined 1018 HR carbon steel (100X)



Non-ultrasonic

Ultrasonic

2024-T6 Aluminum Alloy



Non-ultrasonic

Ultrasonic

1018 Carbon Steel

Figure 7. Representative chips from the machining of aluminum and steel alloys.

ceased with ultrasonic activation and was initiated again when the ultrasonics was turned off.

Pursuant to these demonstrated benefits, prototype ultrasonic tool posts for both external and internal turning were designed and fabricated (Ref. 2). These systems were effectively used in a production environment and confirmed the previously noted effects. Cost effectiveness studies on the process have not been undertaken, but the results obtained offered persuasive evidence of potential significant cost savings.

C. ULTRASONIC CUTTING THEORY

It has been postulated that two major processes occur during metal cutting (Ref. 3,4): plastic deformation along the shear plane immediately ahead of the tool, and friction between the tool and the workpiece. Investigators have estimated that about three-fourths of the total energy in ordinary machining is associated with shear, while one-fourth is consumed in friction. Both friction and shear create heat, raising the temperature of the workpiece, tool, chip and lubricant.

Ultrasonic application has been demonstrated both to facilitate plastic deformation and to reduce friction. Because of these effects, metal is formed more readily under ultrasonic influence by such processes as extrusion, tube and wire drawing, rolling, draw ironing, and the like, wherein reduced forces and increased processing rates are characteristically obtained (Ref. 5). These same effects are applicable in ultrasonic machining.

Numerous investigations have shown that the yield point of a metal can be significantly reduced under ultrasonic influence. Apparently, the high-frequency vibration lowers the forces required to move dislocations within the crystalline structure and to create new dislocations, so that the metal flows more readily.

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(2) N. Maropis and J. Devine, "Development and Evaluation of Ultrasonic I.D. (Boring) Single-Point Machining System." Research Report 72-7, Aeroprojects Inc., West Chester, PA, February 1972.

(3) M. C. Shaw, "Plastic Flow in the Cutting and Grinding of Materials." Proc. Nat. Acad. Sci., Vol. 40 (1954), p. 394-401.

(4) I. Finne and M. C. Shaw, "The Friction Process in Metal Cutting." Trans. ASME, Vol. 78 (Aug. 1956), p. 1649-1657.

(5) F. R. Meyer, "Engineering Feasibility Study of Ultrasonic Application for Aircraft Manufacture." Research Report 73-15, Aeroprojects Inc., West Chester, PA, Army Contract DAAJ01-72-C-0737 (P1G), September 1973.

In the machining process, this transient softening of the material relieves the workhardening that conventionally occurs in the area immediately ahead of the tool, so that stress distortion, fracture and surface tearing are minimized.

The reduced friction under ultrasonic influence is typified by greater ease in assembling components that are ordinarily difficult to assemble, as in press or interference fitting and in tightening or loosening threaded fasteners in wrenching operations (Ref. 5). Studies made on surface layers of metals subjected to oscillating sliding friction have shown substantially less surface hardening than is obtained by unidirectional sliding. Apparently, the reciprocating action relieves a substantial amount of the distortional stress.

In machining, this reduced friction can thus lead to reduced workhardening of the metal surface and reduced heat build-up in the material, leading to increased cutting rates.

D. ULTRASONIC LATHE CUTTING SYSTEMS

In any ultrasonic system that performs useful work, the flow of energy occurs as follows:

1. Electrical power from a standard power line is delivered to a frequency converter which converts the 50/60 hertz power to the desired high operating frequency of the ultrasonic system.

2. This high-frequency electrical power is applied to the ultrasonic transducer, which converts it to high-frequency vibratory power at the same frequency.

3. The mechanical vibration is transmitted through a coupling system to the tool and thence into the material being processed.

Extensive theoretical and empirical studies have established basic design requirements for systems that will transmit the vibratory energy efficiently with minimum energy losses. Frequency tuning and impedance matching throughout the system are essential.

Although there is a commonality of ultrasonic systems for various uses, each application demands consideration of the specifics for that particular process. The special considerations for ultrasonic machining include:

1. Operating frequency of the system.

2. Mode and direction of tool excitation.

3. Tool and tool holder design.

4. Ultrasonic power level.

The effect of frequency per se is not significant in the range between about 5 kilohertz and 100 kilohertz, but practical considerations bracket a narrower range. The frequency should obviously be above the audible range, i.e., about 15 kilohertz or higher. The higher frequencies are power-limited because of the smaller displacement amplitudes achievable. Frequency also dictates the physical dimensions of the transducer-coupling system required; the higher the frequency, the smaller the system. The practical range for machining is from about 15 to 30 kilohertz.

Investigations have established that the most effective vibratory mode in turning operations is in the direction of the cut, i.e., tangential to the rotating workpiece. Several generations of ultrasonic tool posts operating in this mode have been evolved. A typical design is shown schematically in Figure 8. Figure 9 shows such systems mounted on conventional engine lathes. In both cases, the tool post is clamped to the lathe cross slide and carriage unit.

The tool post, tool holder and tool must fulfill acoustic requirements since they are integral parts of the ultrasonic transmission system. These components must be sufficiently rigid to preclude unacceptable tool deflection. The tool holder, in particular, should not constitute a large mass on the system, since massive tools reduce the vibratory amplitude that can be produced at the tool. All tool posts incorporate force-insensitive mounts which ensure negligible frequency shift and negligible energy loss to the support structure under the variable static loads associated with machining.

The power rating of an ultrasonic system is usually stated in terms of high-frequency (RF) electrical power delivered from the frequency converter to the transducer, because this value is readily measurable. It is not necessarily indicative of the acoustical power delivered to the work. Some power losses occur in the ultrasonic system itself. Piezoelectrical transducers of the type used are about 90 percent efficient in converting electrical to acoustical energy. Some additional energy losses may occur at the interfaces between transducer and coupler and between the coupler and the tool, but with a properly designed acoustic system, these losses are small.

The primary consideration is transmitting acoustic energy effectively from the tool into the work. This involves matching the acoustic terminal impedance of the ultrasonic system to the

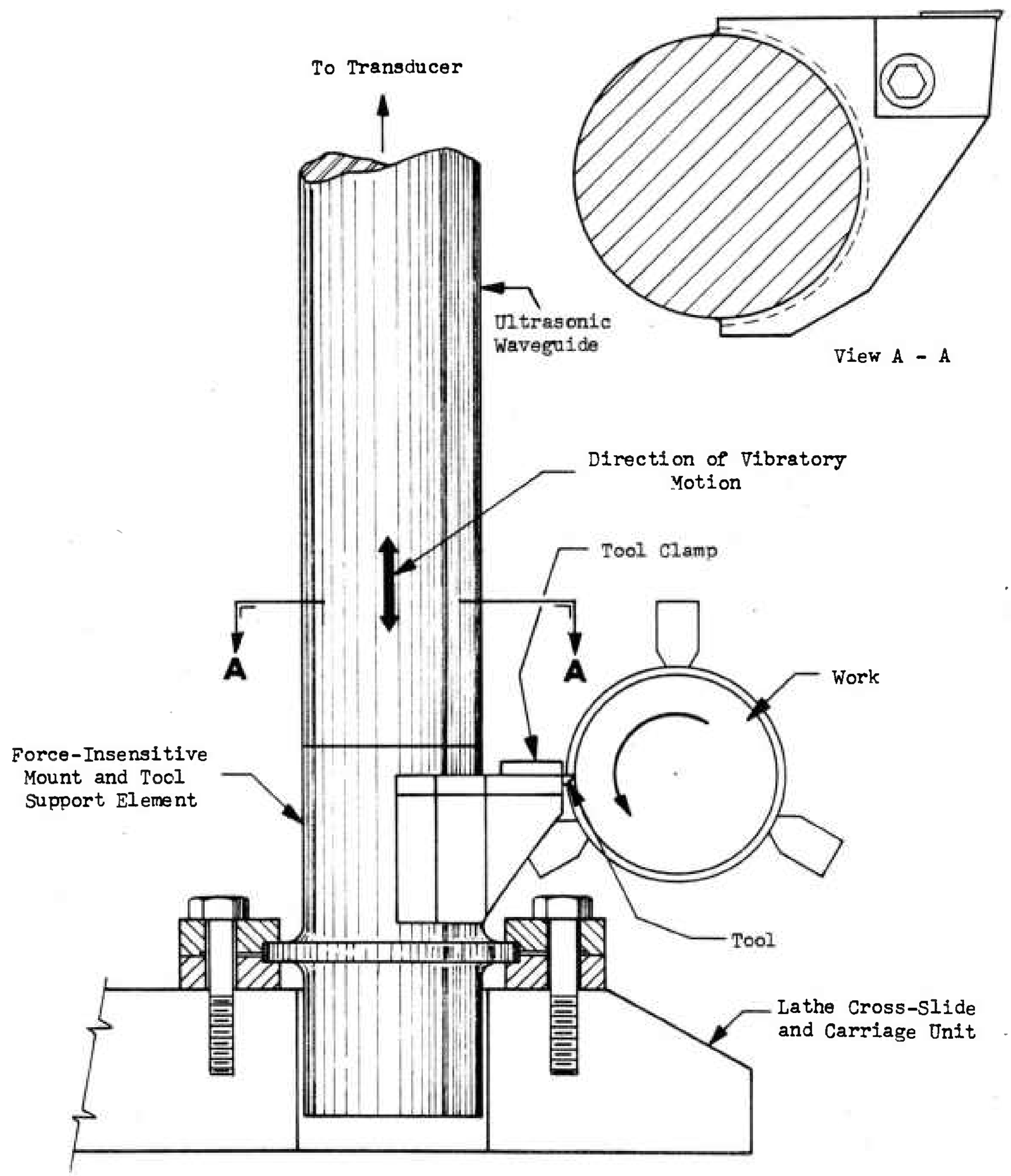


Figure 8. Schematic view of ultrasonic tool post for tangential excitation of the cutting tool.

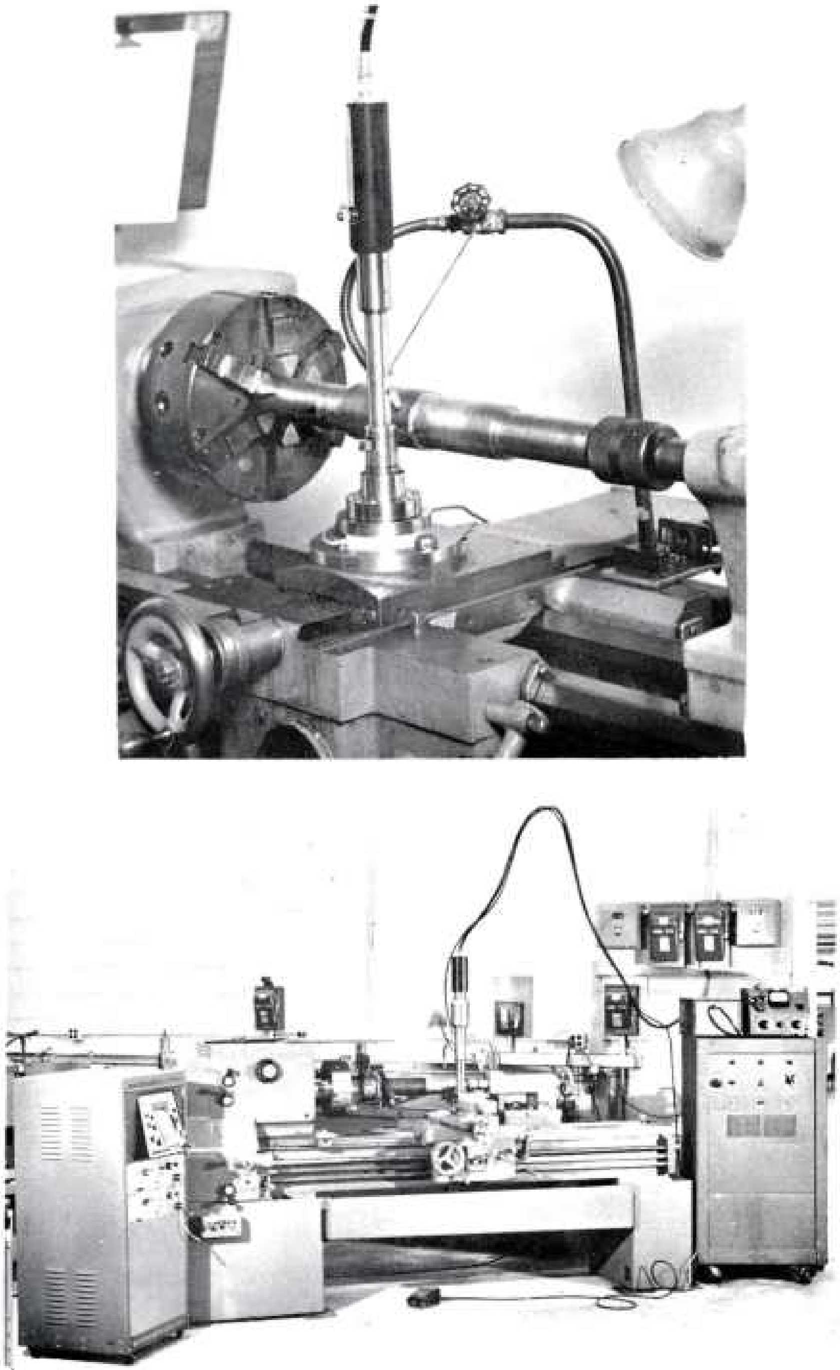


Figure 9. Ultrasonic tool posts mounted on conventional lathes.

impedance of the work. If precise matching is obtained, essentially all of the applied ultrasonic power is transmitted into the work locale. A large difference in these impedance values gives rise to reflections of power at the terminus of the ultrasonic system and limits the power that can be delivered.

The impedance of an ultrasonic system can be determined by a technique involving the use of small piezoelectric type strain gages attached one-quarter wave apart on a uniform section of an ultrasonic wave guide (or coupler). The output of these devices, after appropriate amplification and oscillographic display, yields an elliptical pattern whose area is proportional to the power transmitted through the wave guide. Furthermore, the ratio of the magnitudes of major to minor axes of the ellipse represents the standing wave ratio (SWR). Ideally, this ratio should be 1.0; higher values reflect inefficiencies in ultrasonic energy delivery. Typical oscillographic traces and associated data obtained with one ultrasonic machining system are shown in Figure 10.

An extension of this technique permits measurement of impedance matching into the work and provides a basis for cutting tool design. With one type of tool, for example, it was found that the extent of tool overhang significantly influenced power delivery (see Figure 11). Other tool parameters can be evaluated in a similar manner.

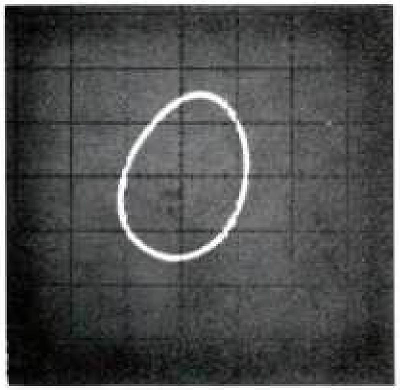
E. APPROACH

Phase I of this ultrasonic machining program involved the design, fabrication, test and evaluation of an ultrasonic system for excitation of an existing production single-point tool turret lathe and installation of this equipment at the facility of an Aerospace contractor designated by the Army. The company selected was Hughes Helicopters, Culver City, CA.

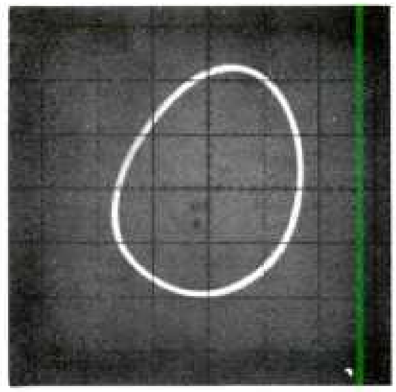
Hughes Helicopters, on the basis of their experience in the fabrication of aircraft materials, provided test bars of several materials selected on the basis of machinability problems. Hughes also provided the necessary cutting tools and tool holders and supplied consultative services throughout this initial phase.

Sonobond designed, fabricated and tested the required ultrasonic array and conducted preliminary cutting trials on the selected materials. Evaluation was made of ultrasonic versus non-ultrasonic cuts, primarily in terms of rate of material removal and tool wear.

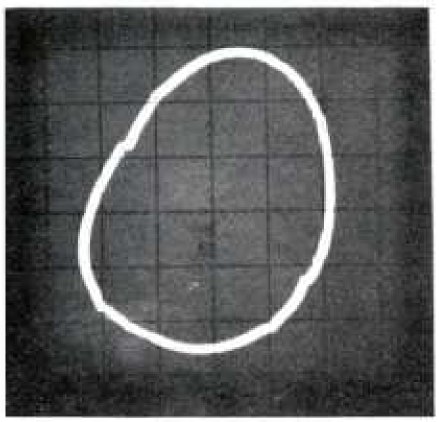
It was initially planned that Phase I would be concluded



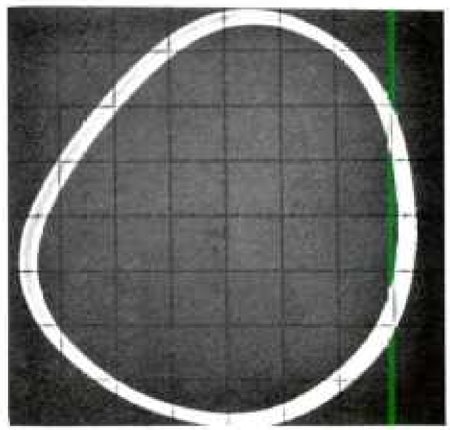
Power In: 50 watts
Power Out: 35 watts
Through Link: 42 watts
SWR: ≈1.4
Area: 4.4 cm^2



Power In: 105 watts
Power Out: 81.5 watts
Through Link: 85.6 watts
SWR: ≈1.35
Area: 9.16 cm^2



Power In: 180 watts
Power Out: 115 watts
Through Link: 143.9 watts
SWR: ≈1.29
Area: 15.67 cm^2



Power In: 345 watts
Power Out: 220 watts
Through Link: 275 watts
SWR: ≈1.13
Area: 32.25 cm^2

Figure 10. Typical oscillograms showing ultrasonic power delivery with one ultrasonic machining system.

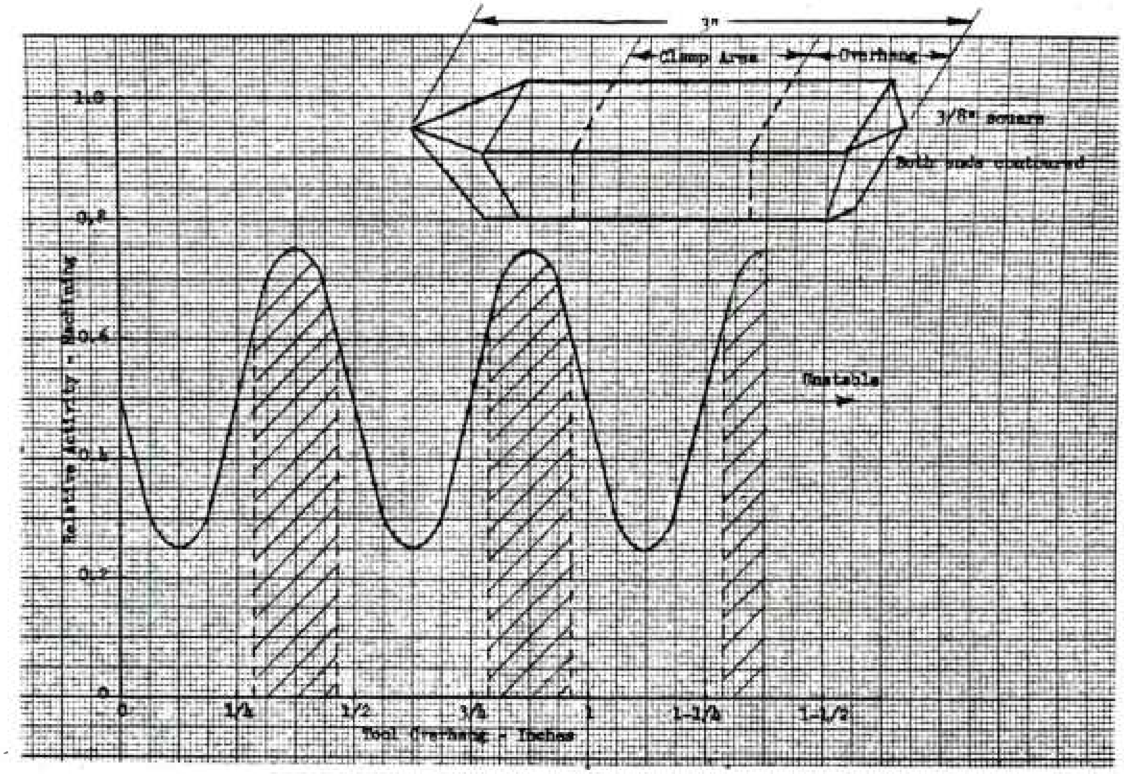


Figure 11. Typical relationship of tool overhang to performance in ultrasonic machining.

with shipment of the ultrasonic system to Hughes Helicopters and installation on a turret lathe at that facility. However, the preliminary efforts indicated the advisability of modifying the ultrasonic system for more effective operation in a production environment. Shipment of the equipment was therefore delayed pending completion of such modifications.

II. EQUIPMENT

The first task of the machining program was to design and assemble an ultrasonic lathe cutting system, which consisted of a tool post capable of performing single-point metal cutting operations on an existing turret lathe; and a frequency converter of sufficient capacity to supply the required high-frequency electrical energy to the ultrasonic tool post. Appropriate interfacing of the tool post with the lathe to provide maximum efficiency of energy delivery to the work was an important part of this activity.

A. LATHE EQUIPMENT

The ultrasonic system was projected for installation on an existing lathe at the Hughes Helicopters' facility. The selected lathe was a Warner & Swasey Model 3A turret lathe (Figure 12). This was a 30-horsepower saddle-type lathe with the indexing handle located on the side of the saddle and the mechanism for 90-degree rotation below the cross slide. The standard tool post on this lathe was the Warner & Swasey open square turret No. 1966-12, a 7-inch-square tool post with the capacity for four 1-inch-square tool holders and mechanically replaceable tool inserts.

A lathe of this type was not available at Sonobond and initial evaluation was carried out on an existing 7-horsepower LeBlond engine and diemaker lathe (Figure 13). Integration of the ultrasonic system with both lathes presented no major problems.

B. ULTRASONIC SYSTEM

The design of an effective ultrasonic tool post for a turret type installation involved an extension of the technology developed earlier which delineated the requirements for such a system. Basically, the system consisted of an ultrasonic transducer to generate the high-frequency vibration and an acoustic coupling system to transmit the vibratory energy to the tool holder and tool insert.

Initially consideration was given to the operating frequency and required power rating of the ultrasonic system. The frequency selected was 15 kilohertz, which would provide maximum amplitude of vibration within an acceptable noise level.

Past experience had shown that the ultrasonic power level, to have an appreciable effect in ultrasonic cutting, should be about 15 to 20 percent of the mechanical power level required to perform the task. Based on this empirical ratio, the ultrasonic system power capacity for a 30 horsepower lathe should

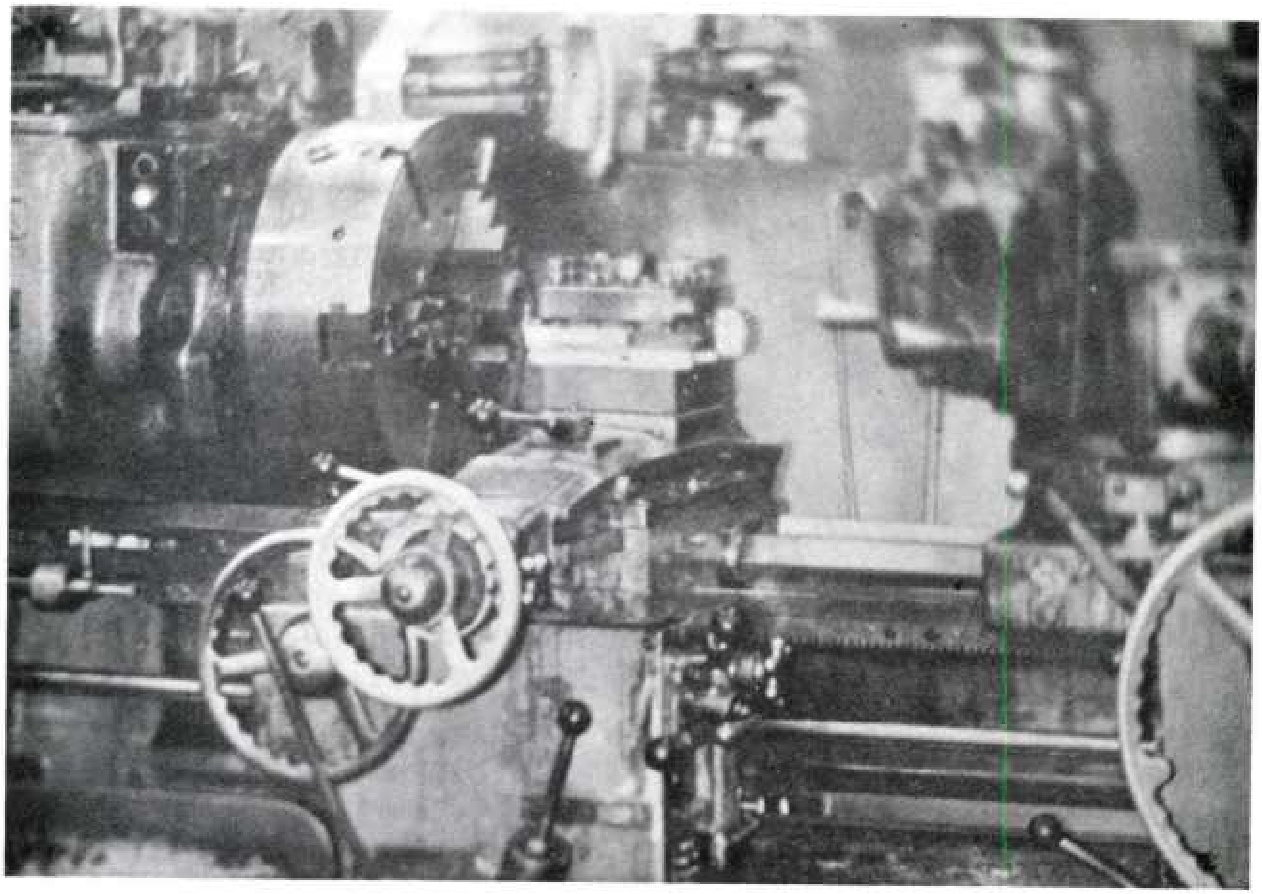


Figure 12. Typical Warner & Swasey Model 3A turret lathe.

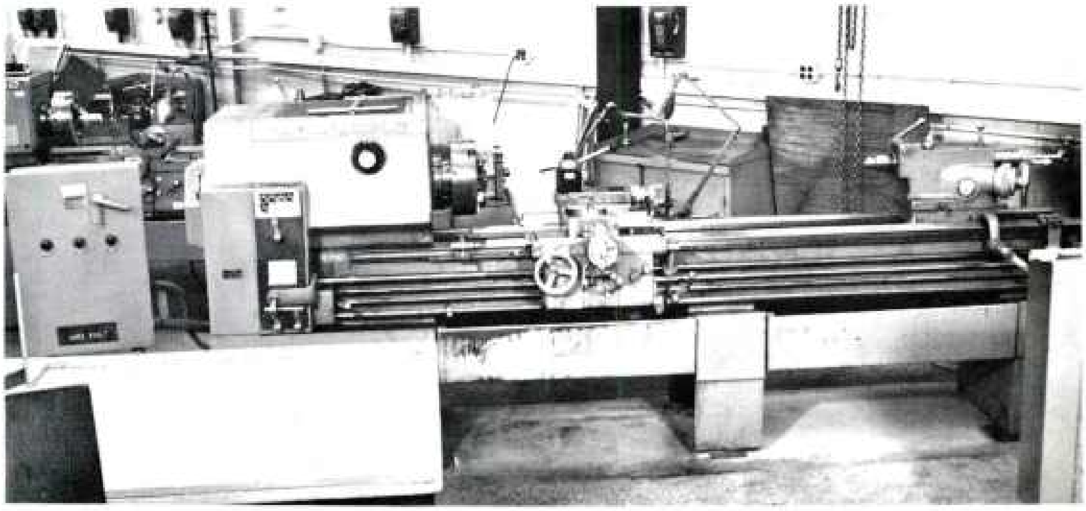


Figure 13. 7-Horsepower, 16-inch-swing LeBlond tool and diemaker lathe.

be within the range of 3375 to 4500 watts. For the LeBlond lathe of 7 horsepower capacity, the required ultrasonic power would be within the range of about 800 to 1050 watts.

Accordingly, it was decided to design the system for operation at 15 kilohertz and 4000 watts. An ultrasonic transducer and matching frequency converter at these ratings are standardly used in Sonobond's largest commercial ultrasonic spot welder, so these component designs were immediately available.

The standard 4000-watt piezoelectric transducer (Figure 14) consisted of disks of lead zirconate titanate polarized in the thickness mode, incorporated in a rugged assembly of the tension shell type with a bias compressive stress on the ceramic disks to preclude failure under dynamic stress. Cooling channels permitted cooling air flow through the assemblies to prevent overheating and depolarization of the transducer elements.

A coupler or wave guide to operate at the 15 kilohertz design frequency was designed and fabricated. This component incorporated a force-insensitive mount to isolate the system from the lathe bed.

Figure 15 shows schematically the final design of the ultrasonic tool post and Figure 16 shows the system mounted on the LeBlond lathe.

The frequency converter (Figure 17) was a hybrid-junction transistorized solid-state device consisting of an amplifier and oscillators to supply the high-frequency electrical power to the transducer. The output frequency of the system could be fine-tuned to precisely match the operating frequency of the transducer-coupling system. The frequency was ultra-stable ($\pm$ 1%) to ensure repeatability. The unit was triple protected for line current, RF power overload and thermal overheat. Cooling fans provided forced circulation of air through the system.

The specifications of the ultrasonic equipment are summarized in Table 1.

C. <u>LATHE INTERFACE</u>

For mounting of the ultrasonic system on the turret lathe, an unfinished forging of the standard turret No. 1966-12 was obtained from Warner & Swasey. The upper part of this forging was removed and the lower part was machined by Warner & Swasey to provide a proper fit into the Model 3A lathe. This lower section (Figure 18) served as a base on which the ultrasonic system was mounted.

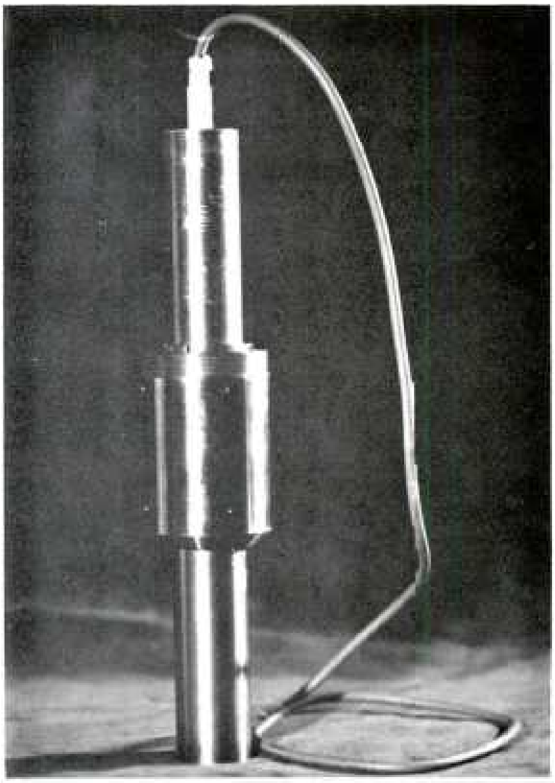


Figure 14. Piezoelectric tension-shell transducer with 4000 watts power rating.

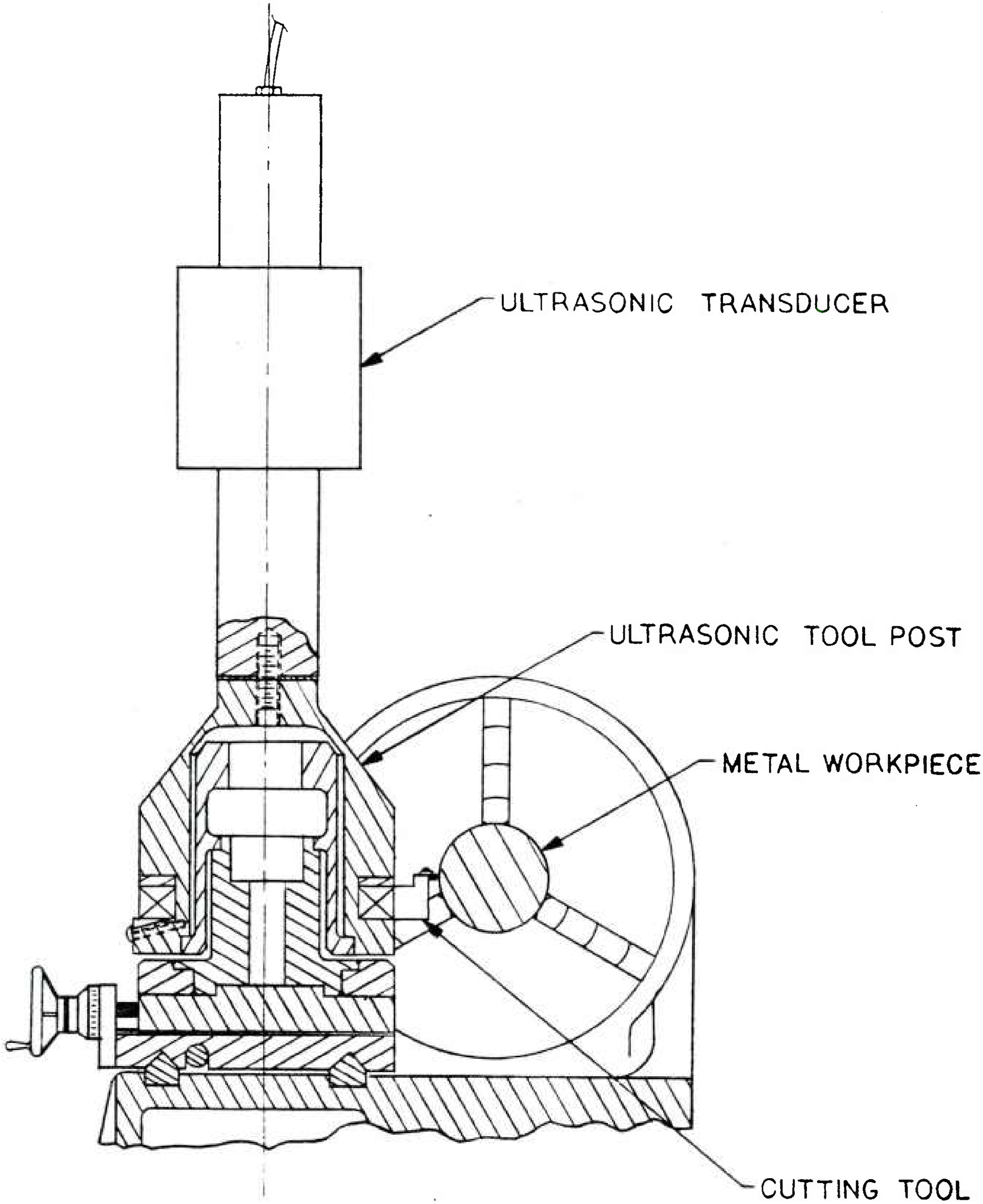


Figure 15. Ultrasonic tool post for turret lathe.

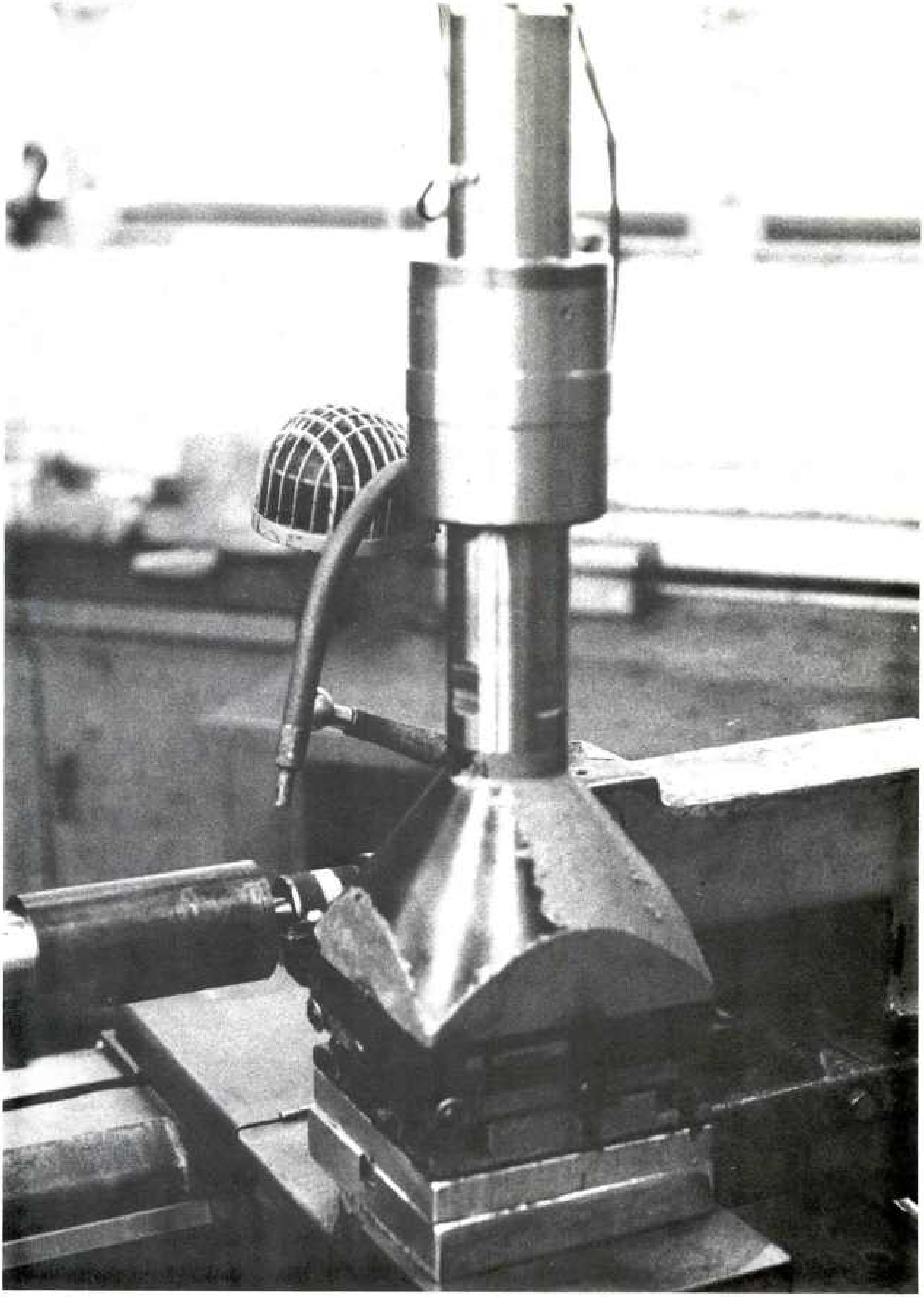


Figure 16. Ultrasonic tool post mounted on cross slide of LeBlond engine lathe.

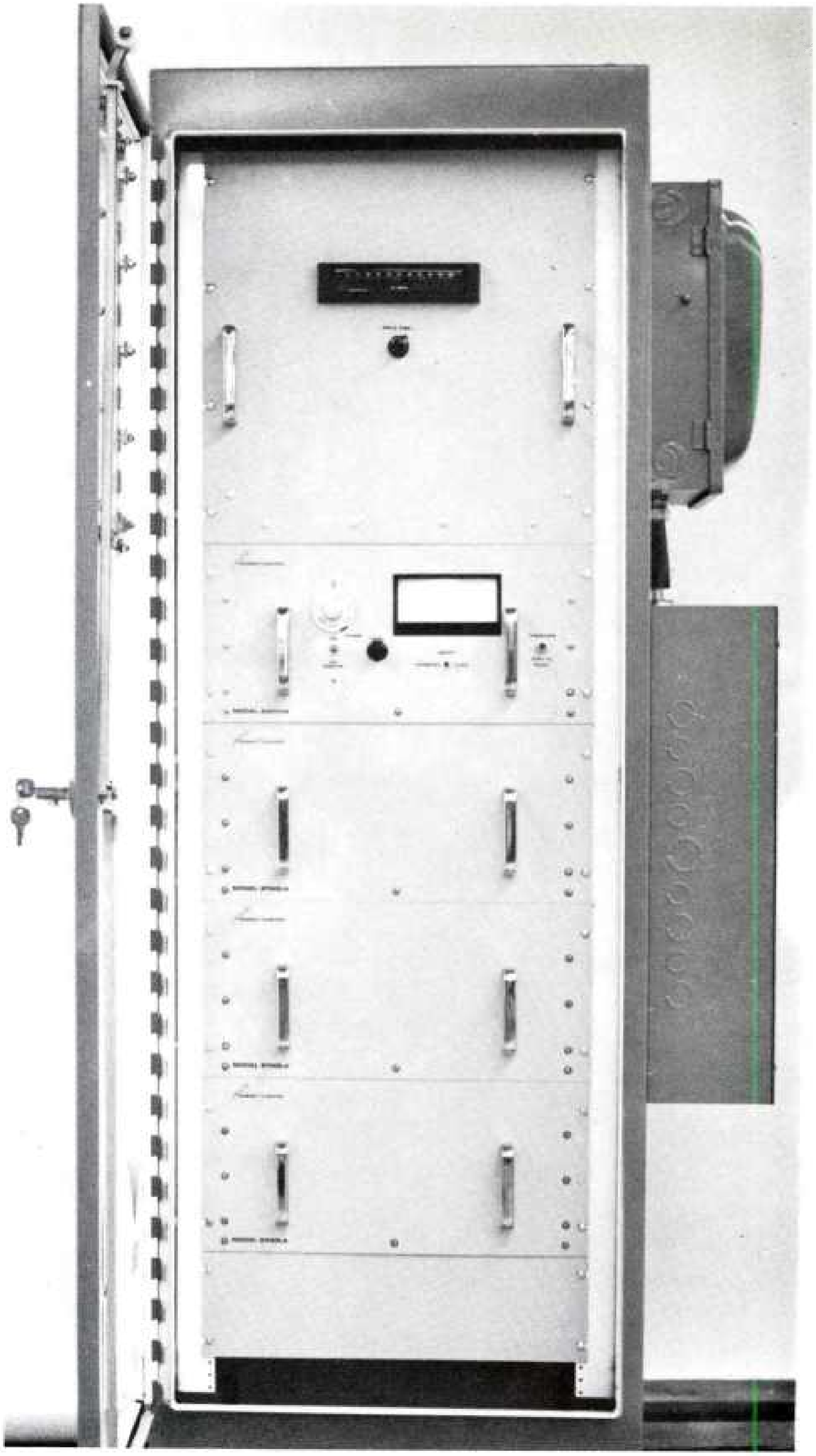


Figure 17. 4000-Watt ultrasonic frequency converter (with front door open).

TABLE 1. ULTRASONIC EQUIPMENT SPECIFICATIONS

TRANSDUCER

Type: Piezoelectric ceramic, tension shell design.

Frequency: 15 kilohertz nominal.

Power Capacity: 4.2 kilowatts continuous duty.

Cooling Air Requirement: 60 psi of clean dry air ($2^{o}C$ dew point) at 2 scfm.

Size: 17 inches long by 4.5 inches maximum diameter.

Weight: 40 pounds.

TOOL POST

Construction: Coupler, force-insensitive mount, locking coupler and base support of high-strength steel.

Tool Provisions: Capable of accepting four standard 1-inch-square tool holders.

Interface with Lathes: Adaptable to Warner & Swasey Model 3A turret lathe and LeBlond engine lathe.

FREQUENCY CONVERTER

Input Power Requirement: 480 volts, 50/60 hertz, three-phase, 30 amperes.

Frequency: 15 kilohertz nominal.

Output Power: 4.2 kilowatts maximum into matched resistive load; continuously variable from 300 to 4200 watts.

Cabinet Size: 30 inches wide x 75 inches high x 27 inches deep.

Weight: 800 pounds.

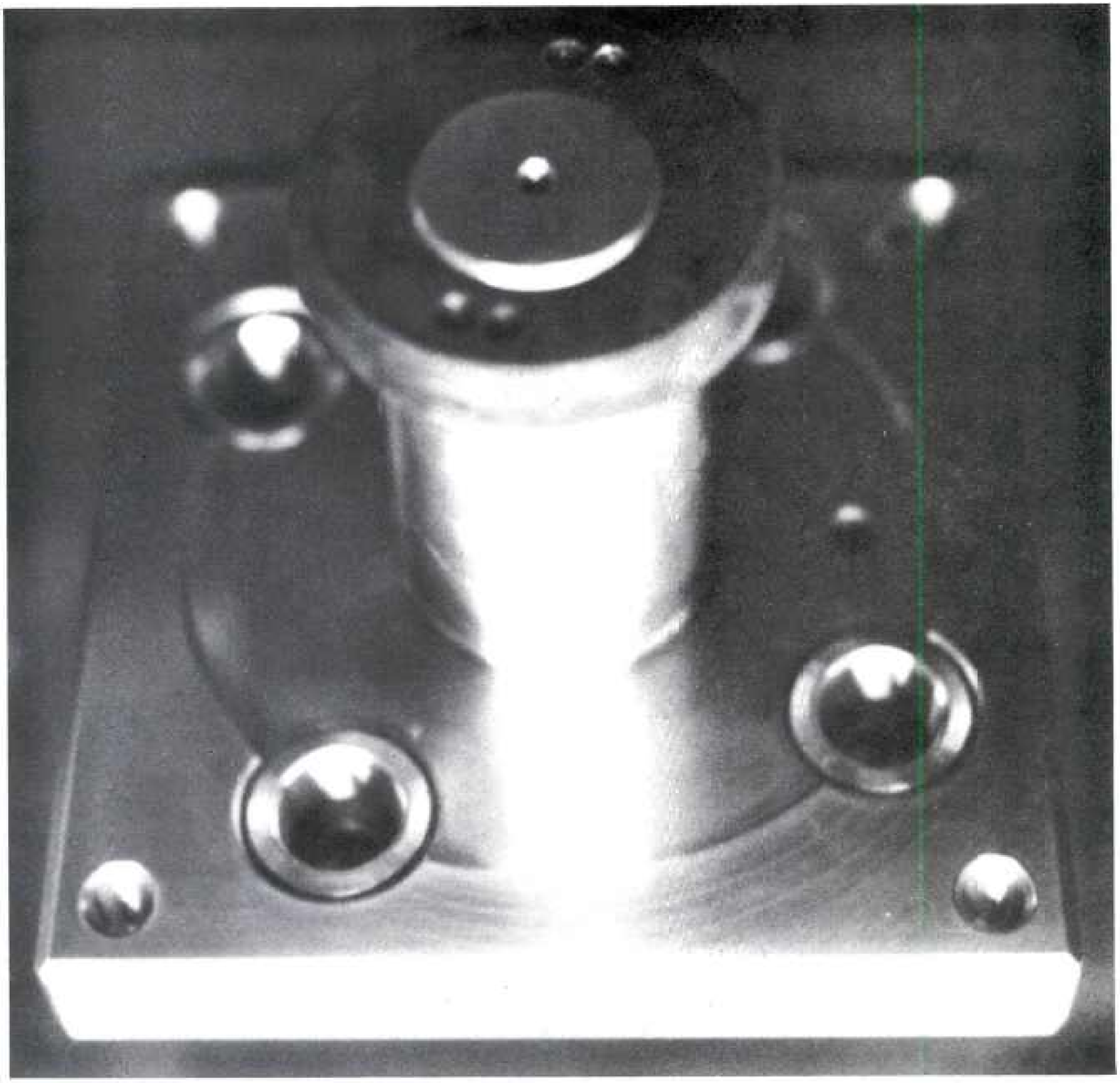


Figure 18. Tool post adaptor to fit Warner & Swasey Model 3A lathe.

For initial evaluation on the LeBlond engine lathe, a set of adaptor plates was fabricated to permit attachment of the ultrasonic tool post to the cross slide of this lathe.

D. TOOL HOLDERS AND INSERTS

The tool holders and tool inserts were selected and supplied by Hughes Helicopters as representative of styles and grades commonly used in their production operations for cutting materials ordinarily difficult to machine. These tools were manufactured by Valenite, Division of Valeron Corporation, Madison Heights, MI.

The geometry of the tool holders, Valenite Style HPC-TGR-16-4, is shown in Figure 19. This tool holder incorporated qualified locating surfaces for the tool inserts and each was supplied with a shim seat and lock screw for attachment of the inserts.

The tool inserts were of a type and material frequently utilized in machining problem materials. They were made of tungsten carbide base with 10% cobalt. Four types were supplied by Hughes Helicopters:

Grade C-2, Valenite TNMM-432ER

Grade C-24, Valenite TNMM-432ER

Grade C-7, Valenite TNMG-432

Grade C-55, Valenite TNMG-432

The geometries of these inserts are shown in Figure 20. Most of the machining work was done with the Grade-2 insert.

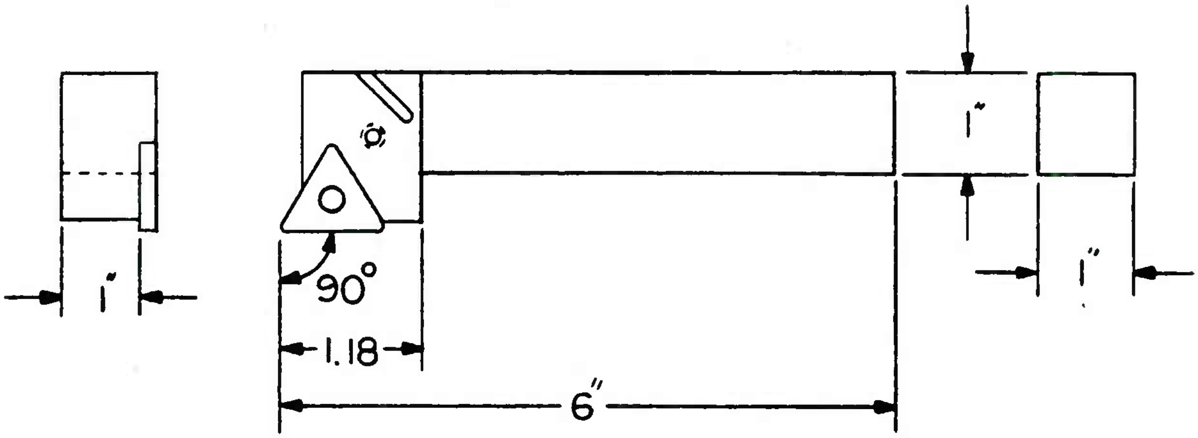


Figure 19. Geometry of tool holder used with ultrasonic tool post.

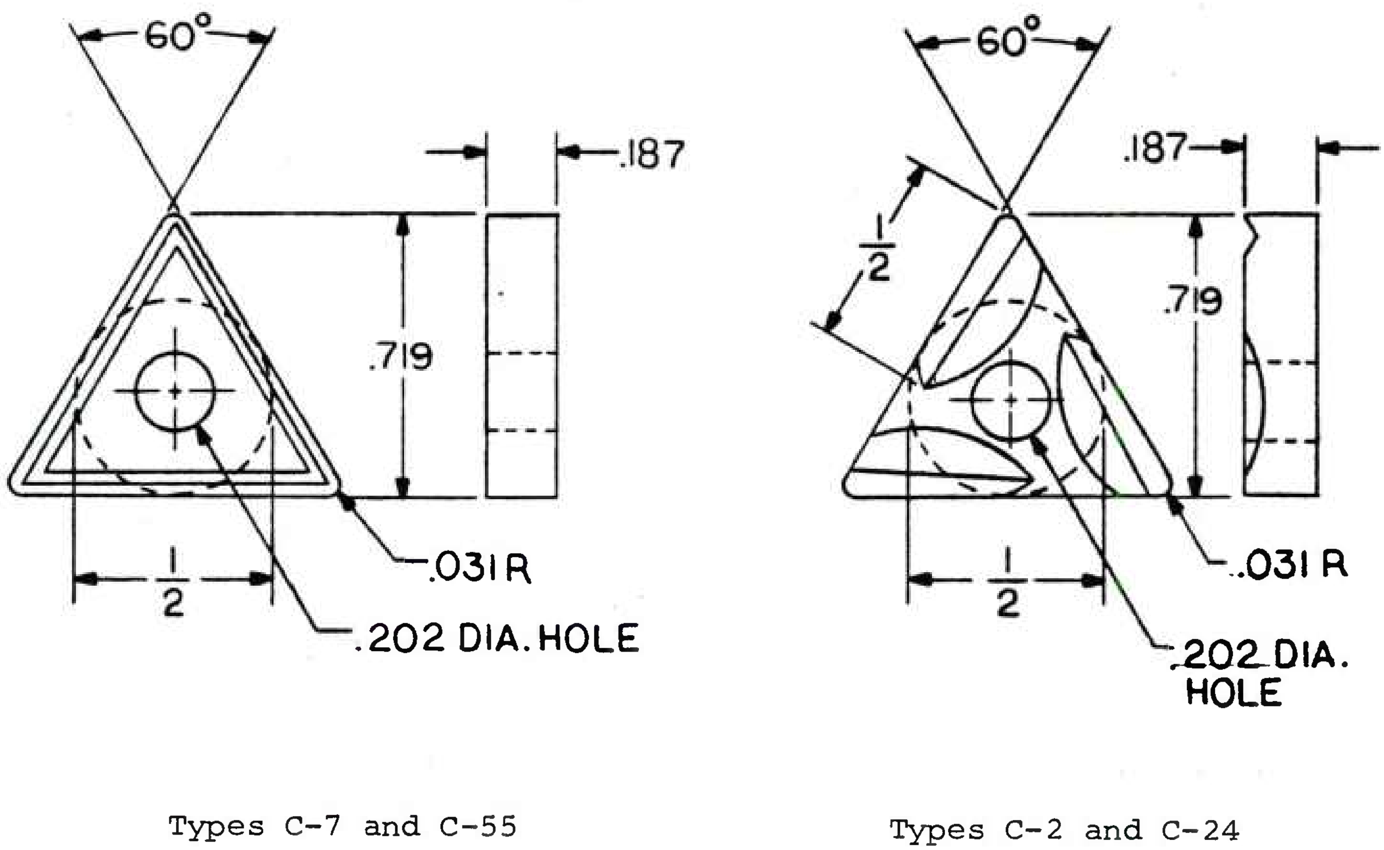


Figure 20. Geometries of tool inserts used.

III. MATERIALS FOR EXPERIMENTAL INVESTIGATION

The basic materials for evaluation of ultrasonic cutting were selected by joint consultation involving the Army, Hughes Helicopters and Sonobond Corporation. These were:

9310 low-carbon steel

4340 medium-carbon steel

17-4 PH stainless steel

ESR 4340 electroslag refined steel

6Al-4V titanium alloy.

These materials were recognized to present machining problems, especially in terms of slow material removal rate, rapid tool wear, or difficulties in attaining acceptable surface finish.

Bars of these materials, usually 3 inches in diameter by 15 inches long, were supplied by Hughes Helicopters each in the heat-treat condition characteristic of the state in which it is used in fabrication of aircraft components. For example, Ti-6Al-4V alloy was supplied in the annealed condition because it is generally used in this state. The steel alloys were all heat treated to the desired hardness.

Additional materials were supplied by other companies interested in ultrasonic machining and it was agreed that the data should be reported herein. Pratt & Whitney Aircraft Group, East Hartfod, CT, supplied some bars of titanium/aluminum alloys--Ti-Al and Ti-3Al-- which are generally not readily machinable. Westinghouse Electric Company, Turbine Components Plant, Winston-Salem, NC, provided bars of Refractaloy 26, a material used for turbine shafts. This material is capable of being machined, but cutting tool wear is excessive.

Pertinent data on the above materials are provided in Table II.

TABLE 2. EXPERIMENTAL CUTTING MATERIALS

Alloy	Type	Hardness (R_C)	Bar Size Dia. (in.)	Bar Size Length (in.)
9310	Low-carbon steel, wrought	32*	3	15
4340	High-strength, medium carbon steel, wrought	29*	3	15
17-4 PH	Precipitation-hardening stainless steel, wrought	39*	3	15
ESR 4340	Electroslag refined high-strength steel, wrought	52-54	3	25½
Ti-6Al-4V	Alpha-beta titanium alloy, wrought	38	3	15
Ti-Al	Alpha-phase titanium alloy, wrought	--	3½	3-7/8
Ti-3Al	Alpha-phase titanium alloy, wrought	--	3¼	7½
Refractaloy 26	Heat-resistant nickel-base alloy, wrought	35	2.6	Various

*Measured hardness.

IV. EXPERIMENTAL INVESTIGATIONS

A. PROCEDURE

After assembly of the ultrasonic equipment, it was installed on the 7-horsepower LeBlond engine lathe and was checked out acoustically and mechanically to ensure satisfactory operation. Essential modifications were made as the work proceeded.

Bars of the material to be machined were turned on the lathe under selected cutting conditions both with and without ultrasonic application. Baseline data for conventional (non-ultrasonic) cutting of some of these materials were obtained from the Machining Data Handbook (Ref. 6). Such data were available for 9310 steel, 4340 steel, 17-4 PH steel and 6Al-4V titanium alloy. For the remaining materials, cutting conditions were selected empirically or at the recommendation of the material suppliers.

The lubricant/coolant, used in some of the finish machining experiments, was Polar Chip 336F, from Polar Chip Incorporated, Santa Fe Springs, CA. This lubricant/coolant was mixed with water in a 1:15 ratio.

Data were recorded for the cutting speed in surface feet per minute (SFM), calculated from rod diameter and rotational speed in revolutions per minute (RPM), feed rate in inches per revolution (ipr) and depth of cut in inches. These data were used to calculate the rate of material removal in cubic inches per minute ($in.^3/min.$) (SFM x 12 x ipr x depth of cut). Ultrasonic power level was also recorded in all runs. For evaluation of surface finish, the cut surfaces were scanned with a Brush Surfindicator, as shown in Figure 21.

B. GENERAL OBSERVATIONS

The results of these evaluations of ultrasonic machining generally confirmed the results obtained earlier with more readily machinable materials. Non-ultrasonic cutting was frequently characterized by tool chatter, which was virtually eliminated with ultrasonic activation. This phenomenon was audibly apparent whenever ultrasonics was turned on or off during a particularly heavy cut. The chips from non-ultrasonic cutting were sometimes blue or burnished: no such discoloration was apparent with the ultrasonically cut chips, indicating the absence of detrimental overheating of the tool and the work material.

Ultrasonics substantially accelerated the rate of material removal with these difficut-to-machine materials, and tool wear was reduced. Data on these effects are provided below.

(6) Machinability Data Center, Metcut Research Associates Inc., Cincinnati, OH, Second Ed., 1972.

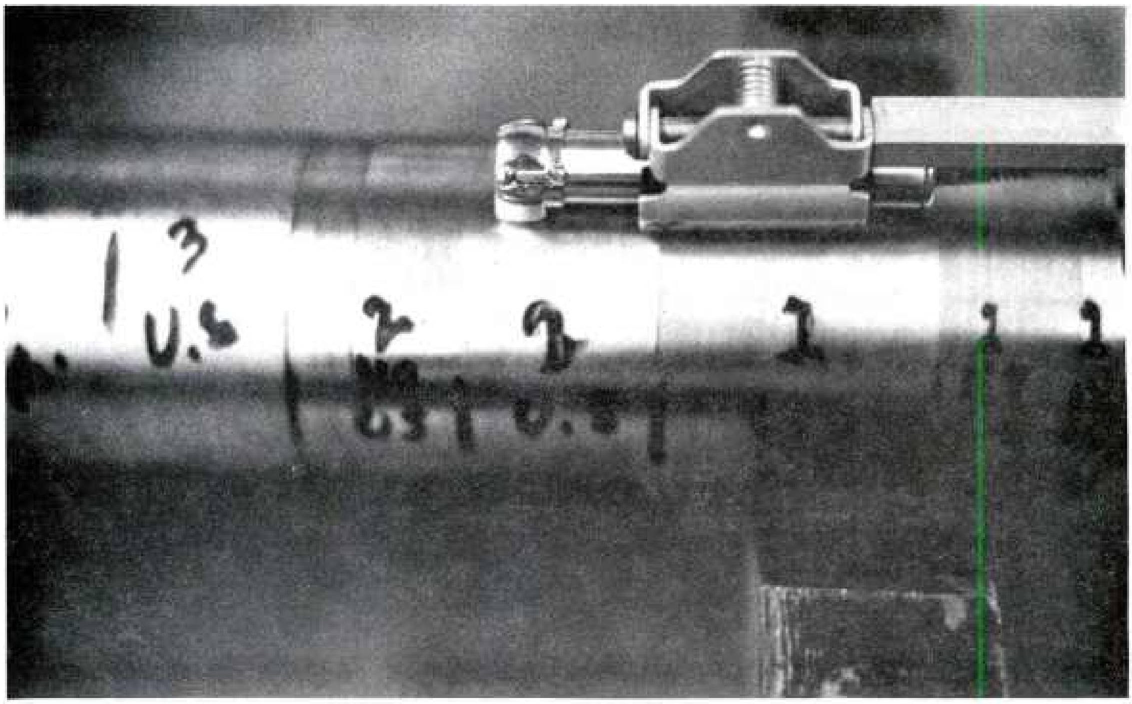


Figure 21. Scanning the surfaces of machined bars with profilometer of Brush Surfindicator.

Breakage of the carbide tool insert occured under certain cutting conditions, apparently because the capability of the 7-horsepower lathe was being exceeded. Such breakage usually occured more readily with the non-ultrasonic than with the ultrasonic cutting. In some instances, the tool broke instantaneously when the ultrasonic system was turned off during a cut. This suggests that the tool loads were lower with ultrasonic activation.

C. SURFACE FINISH

Controlled experiments were made with four materials to evaluate the ultrasonic effect on surface finish. Cuts were made at slow material removal rates characteristic of finish cuts. These experiments were carried out with and without lubricant/coolant, without ultrasonics and at ultrasonic power levels of 1000 and 2000 watts. The results are provided in Table 3.

These data show no consistent pattern of an ultrasonic effect on surface finish. In some instances, the surface finish was smoother and in others it was rougher with ultrasonic application. There appeared to be a trend toward improved finish when the coolant was used at 1000 watts ultrasonic power, as if the vibratory energy aided in pumping the liquid into and out of the cut, but the ultrasonics did not always effect improvement.

Surface finish data obtained sporadically on rough machine cuts likewise showed inconsistencies that could not be explained. This effect requires further evaluation after equipment modification as suggested later in this report.

D. MATERIAL REMOVAL RATES

One of the major demonstrated effects of the ultrasonic assist to machining was the substantially increased rates of material removal. It was possible to increase both the cutting speed and the depth of the cut. Data for the various materials are provided in Tables 4 through 9.

1. 9310 STEEL (Table 4)

With this material, the rate of metal removal was increased from 14.04 cubic inches per minute, as recommended for conventional cutting, to 24.75 cubic inches per minute with ultrasonics, an improvement factor of 1.76. Although tool breakage occured at some of the higher removal rates, this was attributed to limitations of the lathe and not the ultrasonic system.

2. 4340 STEEL (Table 5)

TABLE 3. SURFACE ROUGHNESS DATA

Material	Lubricant	Speed (SFM)	Feed (ipr)	Depth of Cut (in.)	Removal Rate ($in.^3/min$)	Ultrasonic Power (watts)	Surface Roughness ($\mu in.$)
9310	With	514	0.007	0.025	1.08	0	72
	With	514	0.007	0.025	1.08	1000	70
	With	514	0.007	0.025	1.08	2000	68
	Without	514	0.007	0.025	1.08	0	85
	Without	514	0.007	0.025	1.08	1000	85
	Without	514	0.007	0.025	1.08	2000	88
4340	With	388	0.007	0.025	0.81	0	69-70
	With	388	0.007	0.025	0.81	1000	65
	With	388	0.007	0.025	0.81	2000	69-70
	Without	388	0.007	0.025	0.81	0	65
	Without	388	0.007	0.025	0.81	1000	67
	Without	388	0.007	0.025	0.81	2000	72
17-4 PH	With	275	0.005	0.025	0.41	0	40
	With	275	0.005	0.025	0.41	1000	40
	With	275	0.005	0.025	0.41	2000	35
	Without	275	0.005	0.025	0.41	0	56
	Without	275	0.005	0.025	0.41	1000	52
	Without	275	0.005	0.025	0.41	2000	50
Ti-6Al-4V	With	210	0.007	0.025	0.44	0	100-175
	With	210	0.007	0.025	0.44	1000	85
	With	210	0.007	0.025	0.44	2000	160
	Without	210	0.007	0.025	0.44	0	140
	Without	210	0.007	0.025	0.44	1000	225
	Without	210	0.007	0.025	0.44	2000	215

TABLE 4. CUTTING DATA FOR 9310 STEEL

Tool Insert: VC-2

Speed (SFM)	Feed (ipr)	Depth of Cut (in.)	Removal Rate (in^3/min)	Ultrasonic Power (watts)	Comments
390.0	0.020	0.150	14.04	0	Reference data*
68.9	0.005	0.250	1.03	1200	Good cut.
68.9	0.007	0.250	1.45	1200	Good cut.
68.9	0.009	0.250	1.86	1200	Good cut.
68.9	0.013	0.250	2.69	1200	Insert & shim broke.
95.7	0.005	0.250	1.44	1200	Good cut.
95.7	0.007	0.250	2.01	1200	Good cut.
95.7	0.009	0.250	2.58	1200	Good cut.
95.7	0.013	0.250	3.73	1200	Good cut. Tip broke when U/S was turned off.
129.8	0.005	0.250	1.95	1200	Good cut.
129.8	0.007	0.250	2.73	1200	Good cut.
129.8	0.009	0.250	3.50	1200	Good cut.
129.8	0.013	0.250	5.06	1200	Good cut.
185.7	0.005	0.250	2.79	1200	Good cut.
185.7	0.007	0.250	3.90	1200	Good cut.
185.7	0.009	0.250	5.01	1200	Good cut.
185.7	0.013	0.250	7.24	1200	Good cut.
254.6	0.005	0.250	3.82	1200	Good cut.
254.6	0.007	0.250	5.35	1200	Good cut.
254.6	0.009	0.250	6.87	1200	Good cut.
254.6	0.013	0.250	9.93	1200	Good cut.
358.3	0.005	0.250	5.37	1200	Good cut.
358.3	0.007	0.250	7.52	1200	Good cut.
358.3	0.009	0.250	9.67	1200	Good cut.
358.3	0.013	0.250	13.97	1200	Good cut.
474.3	0.005	0.250	7.11	1200	Good cut.
474.3	0.007	0.250	9.96	1200	Good cut.
474.3	0.009	0.250	12.81	1200	Good cut.
474.3	0.013	0.250	18.50	1200	Tip broke.
634.6	0.005	0.250	9.52	1200	Good cut.
634.6	0.007	0.250	13.33	1200	Good cut.
634.6	0.009	0.250	17.13	1200	Good start; lathe stalled & tip broke.
634.6	0.013	0.250	24.75	1200	Tip broke.

*Machining Data Handbook (Ref. 6).

TABLE 5. CUTTING DATA FOR 4340 STEEL

Tool Insert: VC-2

Speed (SFM)	Feed (ipr)	Depth of Cut (in.)	Removal Rate ($in.^3/min$)	Ultrasonic Power (watts)	Comments
280.0	0.015	0.150	7.56	0	Reference data*.
514.0	0.007	0.250	10.79	1200	Good cut.
514.0	0.009	0.250	13.88	1200	Lathe began to stall; power increased to 1700 w, then decreased to 1200 w. Good cut.
514.0	0.009	0.250	13.88	1200	Good cut.
736.5	0.007	0.250	15.47	1200	Tip broke.
736.5	0.009	0.250	19.89	1200	Lathe stalled and tip broke.

*Machining Data Handbook (Ref. 6)

Good cuts on the 4340 steel were obtained at removal rates up to 15.47 cubic inches per minute, compared to a recommended rate of 7.56 cubic inches per minute. The improvement factor here was 2.05.

3. 17-4 PH STAINLESS STEEL (Table 6)

A substantially greater effect was obtained with this material. A low removal rate of 3.42 cubic inches per minute was recommended. Ultrasonics permitted cutting at rates up to 25.02 cubic inches per minute, an improvement factor of 7.32. Stalling of the lathe became a factor at the higher cutting rates.

4. ESR 4340 STEEL (Table 7)

Baseline data for this material was not available. Accordingly, several cuts were made without ultrasonics. Very low removal rates were obtained, less than 1 cubic inch per minute and these were limited by rapid tool wear. When the ultrasonics was turned on, the improved cutting was immediately apparent and good cuts were obtained at rates up to 4.12 cubic inches per minute.

5. 6Al-4V TITANIUM ALLOY (Table 8)

Recommended machine settings specified a material removal rate of 4.86 cubic inches per minute. With ultrasonics, rates up to 15.14 cubic inches per minute were possible, an improvement factor of 3.17.

6. TITANIUM/ALUMINUM ALLOYS (Table 9)

These alloys were reported to be very difficult to machine by conventional methods and were stated to be subject to severe tearing and surface damage. Good cuts were obtained ultrasonically at a rate of 1.21 cubic inches per minute.

E. TOOL WEAR

Some of the materials investigated, particularly ESR 4340 steel and Refractaloy 26, reportedly induce rapid tool wear and/or breakage in conventional machining. A few experiments were oriented to determining the ultrasonic effect on this phenomenon.

In almost every instance, ultrasonic application substantially increased tool life (Table 10). With the Refractaloy, for example, under one set of conditions the tool broke after 2.5 inches of conventional cutting and after 10.5 inches of ultrasonic cutting. With the maximum removal rate used, 3.92 cubic inches per minute, the tool in conventional cutting was worn 0.07 inch after 4.8 inches of cutting, while that used in

TABLE 6. CUTTING DATA FOR 17-4 PH STEEL

Tool Insert: VC-2

Speed (SFM)	Feed (ipr)	Depth of Cut (in.)	Removal Rate ($in.^3/min$)	Ultrasonic Power (watts)	Comments
190.0	0.010	0.150	3.42	0	Reference data*.
275.9	0.007	0.250	5.79	1200	Good cut.
275.9	0.010	0.250	8.28	1200	Good cut.
201.2	0.016	0.250	9.66	1200	Good cut.
388.3	0.013	0.250	15.14	1200	Good cut.
514.0	0.013	0.250	20.05	1200	Good cut.
580.6	0.013	0.250	22.64	1200	Good cut.
613.7	0.013	0.250	23.93	1200	Good cut, but lathe began to stall.
275.9	0.0065	0.312	6.71	1200	Good cut.
388.3	0.0065	0.312	9.45	1200	Good cut.
388.3	0.009	0.312	13.08	1200	Good cut.
580.6	0.0065	0.312	14.13	1200	Good cut. Tool broke when U/S was shut off.
536.5	0.0073	0.312	14.66	1200	Good cut. Lathe began to labor.
514.0	0.009	0.312	17.32	1200	Good cut.
536.5	0.009	0.312	18.08	1200	Good cut. Lathe stalled.
514.0	0.013	0.312	25.02	1200	Good cut. Lathe began to stall (less with U/S than without).
514.0	0.013	0.312	25.02	2000	Lathe stalled & tool broke.

*Machining Data Handbook (Ref. 6).

TABLE 7. CUTTING DATA FOR ESR 4340 STEEL*

Tool Insert: VC-2 except as noted.

Speed (SFM)	Feed (ipr)	Depth of Cut (in.)	Removal Rate ($in.^3$/min)	Ultrasonic Power (watts)	Comments
242.9	0.005	0.060	0.87	0	Tool burned and broke after 2½".
269.4	0.005	0.060	0.97	0	VC-7 tool; tool burned off after 5/16".
103.8	0.009	0.050	0.56	800	Good cut for 22".
351.7	0.009	0.060	2.28	800	Good cut; some tool wear.
242.9	0.005	0.060	0.87	1200	Good cut.
137.4	0.009	0.060	0.89	1200	Good cut for 3½". No tool wear.
269.4	0.005	0.060	0.97	1200	VC-7 tool; good cut.
196.5	0.009	0.060	1.27	1200	VC-7 tool; some tool wear.
137.4	0.009	0.091	1.35	1200	Good cut for 2½".
101.4	0.013	0.091	1.44	1200	Good cut.
137.4	0.009	0.100	1.48	1200	Good cut.
269.4	0.009	0.060	1.75	1200	Good cut for 2". Slight tool wear.
137.6	0.013	0.091	1.95	1200	Good cut.
269.7	0.005	0.125	2.02	1200	Good cut.
196.7	0.009	0.125	2.66	1200	Some tool wear in 2".
137.6	0.013	0.125	2.68	1200	Good cut.
177.1	0.007	0.187	2.78	1200	Good cut for 1-3/4".
196.7	0.007	0.187	3.19	1200	Good cut.
196.7	0.013	0.125	3.84	1200	Tool broke.
196.7	0.007	0.250	4.12	1200	Good cut.

*No baseline data available.

TABLE 8. CUTTING DATA FOR 6AL-4V TITANIUM ALLOY

Tool Insert: VC-2

Speed (SFM)	Feed (ipr)	Depth of Cut (in.)	Removal Rate ($in.^3$/min)	Ultrasonic Power (watts)	Comments
180.0	0.015	0.150	4.86	0	Reference data*.
74.7	0.005	0.250	1.12	1200	Good cut.
74.7	0.007	0.250	1.57	1200	Good cut.
74.7	0.009	0.250	2.02	1200	Good cut.
74.7	0.013	0.250	2.91	1200	Good cut.
103.8	0.005	0.250	1.56	1200	Good cut.
103.8	0.007	0.250	2.18	1200	Good cut.
103.8	0.009	0.250	2.80	1200	Good cut.
103.8	0.013	0.250	4.05	1200	Good cut.
140.7	0.005	0.250	2.11	1200	Good cut.
140.7	0.007	0.250	2.95	1200	Good cut.
140.7	0.009	0.250	3.80	1200	Good cut.
140.7	0.013	0.250	5.49	1200	Good cut.
201.2	0.005	0.250	3.02	1200	Good cut.
201.2	0.007	0.250	4.23	1200	Good cut.
201.2	0.009	0.250	5.43	1200	Good cut.
201.2	0.013	0.250	7.85	1200	Good cut.
275.9	0.005	0.250	4.14	1200	Good cut.
275.9	0.007	0.250	5.79	1200	Good cut.
275.9	0.009	0.250	7.45	1200	Good cut.
275.9	0.013	0.250	10.76	1200	Good cut.
388.3	0.005	0.250	5.82	1200	Good cut.
388.3	0.007	0.250	8.15	1200	Good cut.
388.3	0.009	0.250	10.48	1200	Good cut.
388.3	0.013	0.250	15.14	1200	Good cut. Tool broke when U/S was turned off.
514.0	0.005	0.250	7.71	1200	Tip broke.
514.0	0.005	0.250	7.71	1200	Tip broke.

*Machining Data Handbook (Ref. 6).

TABLE 9. CUTTING DATA FOR TITANIUM/ALUMINUM ALLOYS*

Tool Insert: VC-2 except as noted.

Speed (SFM)	Feed (ipr)	Depth of Cut (in.)	Removal Rate ($in.^3$/min)	Ultrasonic Power (watts)	Comments
Ti-3Al					
112.4	0.010	0.100	1.35	1100	Tool broke after ½" of cutting.
152.2	0.010	0.100	1.83	1100	Tool burns.
80.8	0.005	0.100	0.48	1100	Good cut.
112.4	0.010	0.030	0.40	1100	Tool broke.
80.8	0.006	0.062	0.36	1100	VC-24 tool. Tool burns.
112.4	0.010	0.025	0.33	1100	VC-55 tool. Tool burns.
80.8	0.005	0.100	0.48	1200	Good cut.
80.8	0.005	0.150	0.72	1200	Good cut.
80.8	0.005	0.200	0.97	1200	Good cut.
80.8	0.005	0.250	1.21	1200	Good cut.
Ti-Al					
87.1	0.005	0.050	0.26	1200	Good cut.
87.1	0.005	0.010	0.52	1200	Good cut.
87.1	0.005	0.200	1.05	1200	Noted damage.

* No baseline data available.

TABLE 10. TOOL WEAR DATA

Speed (SFM)	Feed (ipr)	Depth of Cut (in.)	Removal Rate ($in.^3/min$)	Ultrasonic Power (watts)	Results
Refractaloy 26 (No lubricant)					
96	0.018	0.160	3.32	0	Tool broke after 2.5" cut.
96	0.018	0.160	3.32	1200	Tool broke after 12.5" cut.
96	0.018	0.125	2.59	0	Tool broke after 1.2" cut.
96	0.018	0.125	2.59	1200	0.017" tool wear after 4.5" cut.
113	0.013	0.125	2.20	0	0.03" tool wear after 11" cut.
113	0.013	0.125	2.20	1200	0.03" tool wear after 11" cut.
201	0.013	0.125	3.92	0	0.07" tool wear after 4.8" cut.
201	0.013	0.125	3.92	1200	0.03" tool wear after 5.1" cut.
ESR 4340 Steel (With lubricant)					
242.7	0.005	0.060	0.87	0	Tool burned and broke after 0.3" cut.
242.7	0.005	0.060	0.87	1200	0.014" tool wear after 16.5" cut.

ultrasonic cutting was worn only 0.03 inch after 5.1 inches of cutting.

Even greater effect was obtained with ESR 4340. After 0.3 inch of conventional cutting, the tool burned and broke. In ultrasonic cutting, the tool showed only 0.014 inch of wear after a 16.5 inch cut.

Subsequent data obtained with Refractaloy 26 is presented in Table 11. Here the non-ultrasonic data was obtained with a solid, conventional tool post mounted on the LeBlond lathe. The results are not strictly comparable to results with the ultrasonic tool post. Nevertheless, the favorable trend with ultrasonic activation appeared to be confirmed.

F. CHIP CHARACTERISTICS

Comparison was made of the chips removed from the metal with ultrasonic and non-ultrasonic turning. Typical chips obtained under both conditions are shown in Figure 22. In all instances, the ultrasonic chips were characterized by a much larger curl radius, suggesting that less strain was induced in the chip as a result of ultrasonic activation.

A metallographic analysis of representative chips produced with and without ultrasonic assist was made by Professor Kenneth J. Trigger of the Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, IL. The analysis was made on chips of 4340 steel machined under the following conditions:

Tool insert: VC-2 with molded-in chip curler

Cutting speed: 645 RPM = 514 SFM

Feed: 0.009 ipr

Depth of cut: 0.250 inch

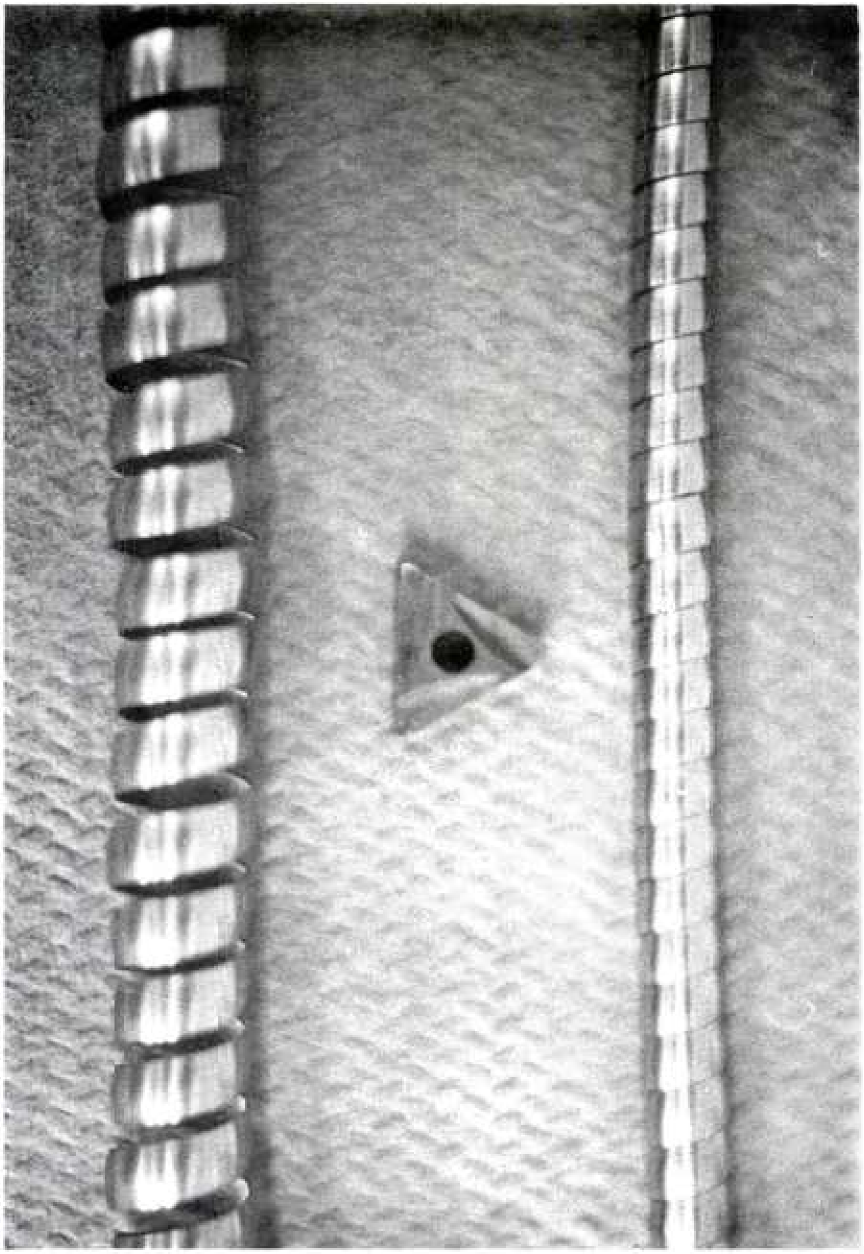
Ultrasonic power: 1200 watts.

Chip samples were examined microscopically and measurements made on the free surface i.e., the side opposite the tool-chip interface. The free surface of a continuous chip (not a so-called brittle chip as in cast iron) is typically a lamella-like array. The spacing of the lamella is dependent upon the shear behavior of the tool, the tool geometry and especially the tool-chip friction at the interface. In this comparison, the only variable was the tool-chip formation.

The chips were examined with a low-power microscope equipped

TABLE 11. ADDITIONAL TOOL WEAR DATA WITH REFRACTALOY 26

Speed (SFM)	Feed (ipr)	Depth of Cut (in.)	Removal Rate ($in.^3$/min)	Ultrasonic Power (watts)	Results
DATA OBTAINED WITH SOLID TOOL POST				(No Ultrasonics)	
135	0.0115	0.125	2.33	0	0.012" wear in 14.75".
176	0.0147	0.125	3.88	0	0.018" wear in 14.25".
160	0.0147	0.125	3.53	0	0.012" wear in 13.75".
143	0.0147	0.125	3.15	0	0.010" wear in 13.25".
173	0.0147	0.125	3.81	0	0.11" wear in 12.75".
DATA OBTAINED WITH ULTRASONIC TOOL POST					
192	0.0115	0.060	1.59	500	Tip flaked off top.
253	0.0115	0.020	0.70	150	0.012" wear in 14.75".
249	0.0051	0.020	0.30	150	Insert chipped.
245	0.0051	0.020	0.30	200	Tool loose in holder.
176	0.0147	0.125	3.88	1400/800	0.010" wear in 14.75".
160	0.0147	0.125	3.53	1600	0.012" wear in 14.25".
143	0.0147	0.125	3.15	1900	0.010" wear in 13.75".
173	0.0147	0.125	3.81	2000	0.006" wear in 13.25".



Ultrasonic Non-Ultrasonic

Figure 22. Typical chips obtained with ultrasonic and non-ultrasonic turning of 4340 steel (VC-2 tool insert shown in center).

with a filar micrometer eyepiece giving an overall magnification of approximately 20X and the lamella spacings were measured. Five to eight measurements, each involving a minimum of 20 lamella, were made on representative samples for each test condition. In addition, the average chip thickness from the tool interface to the midpoint of the free surface was measured. The results were as follows:

a. With ultrasonic assist:

Lamella spacing: 0.0067 - 0.0075 inch.

Average chip thickness: 0.012 - 0.013 inch.

b. Without ultrasonic assist:

Lamella spacing: 0.0085 - 0.0095 inch.

Average chip thickness: Approximately the same as above, but lamella plate projections were higher and less regular.

Chip samples were mounted in bakelite molds, ground and rough-polished for microhardness surveys. Tests were made with a Tukon (Wilson) tester with a 136-degree square base diamond pyramid indenter at 2 kilograms load. Four to six tests were made for each condition. The diamond pyramid hardness (DPH) measurements were as follows:

a. With ultrasonic assist:

Chip surface: 454 - 471 DPH

Chip body: 471 - 485 DPH.

b. Without ultrasonic assist:

Chip surface: 433 - 490 DPH

Chip body: 535 - 560 DPH.

The difference in surface hardness between the two types of samples is neither significant nor conclusive. The lower hardnesses for the chip surfaces in both instances is attributed to the tempering effect of the higher temperature at the tool-chip interface compared to that in the chip body.

The higher chip body hardness in the non-ultrasonic chip is probably due to the higher chip strain as a consequence of high tool-chip friction.

G. DISCUSSION

These preliminary machining studies indicated positive and significant effects of the ultrasonic assist in terms of increased material removal rates and reduced tool wear. The equipment and experimentation satisfied the basic requirements of Phase I of the contract. However, the work also indicated the need for further modification and refinement of the ultrasonic equipment for evaluation in a production environment.

1. TOOL POST REDESIGN

The tool holder retention system which involved an auxiliary clamping device, was adequate for preliminary studies, but occasional shifting of the cutting tool occured and the clamping procedure was too cumbersome and imprecise for production use. An improved, positive tool retention means should be devised to assure maximum ultrasonic energy delivery without shifting of the tool. It is anticipated that a modified wedge will achieve this objective. The effect of such a modification on the entire tool post design, including the force-insensitive mount, should be considered. Interface of the tool post with the Warner & Swasey Model 3A lathe also requires re-evaluation.

2. OPERATIONAL INTERLOCK

Operation of the ultrasonic machining system required the services of two technicians, one to operate the lathe and the other to activate and monitor the ultrasonic system so that ultrasonic energy delivery was coordinated with the instant of tool engagement. A power interlocking system should be incorporated to provide automatic activation of ultrasonic power when the cutting load is initiated.

3. AUTOMATIC FREQUENCY CONTROL

For maximum efficiency of ultrasonic energy delivery, the output frequency of the frequency converter should precisely match the operating frequency of the tool post. This tool post frequency was found to shift slightly as a function of the material being cut and the lathe settings. The frequency converter setting therefore had to be manually adjusted for each test run. The resonant frequency of the tool post (unloaded) was approximately 14,750 hertz and the indicated frequencies varied within the range of about $\pm$ 1 percent of this value.

At the conclusion of this program, the frequency converter was modified to incorporate automatic frequency control so that it would automatically track the frequency of the tool post under load.

4. LOAD MONITORING CIRCUITRY

Most of the work reported herein was performed at an ultrasonic power level of 1200 watts, which was about 23 percent of the LeBlond lathe capacity. This was adequate to obtain the beneficial effects noted. However, actual power delivery into the work varies as a function of tool loading, which affects impedance matching at the tool/work interface. Such matching is a complex function of several factors, including the ultrasonic power introduced, the strain in the cutting tool and the strain in the work material. More consistent results could be obtained with the use of feedback circuitry which would match the ultrasonic power delivery to the tool load and such a system should be developed.

5. EVALUATION ON A PRODUCTION LATHE

The modifications noted above should provide an ultrasonic system that could be realistically evaluated on a production turret lathe such as the Warner & Swasey Model 3A. Such evaluation should include, as a minimum, material removal rate, tool life, surface finish and a detailed analysis of cost effectiveness. Consideration can then be given to modifications required for installing the system on other types of lathes and for interfacing with other lathe subsystems such as numerical control, automatic chucking, tool changers, etc., with the view to optimizing the process with such operations.

CONCLUSIONS

1. Ultrasonic activation of cutting tools greatly facilitated the lathe turning of wrought metal alloys that are ordinarily difficult to machine, including ESR 4340 steel, 9310 steel, 4340 steel, 17-4 PH steel, several titanium alloys and Refractaloy 26.

2. Rates of material removal for these alloys were increased by factors ranging from about 175 percent to more than 700 percent with ultrasonic assist.

3. Both cutting speed and depth of cut were substantially increased over recommended standard cutting parameters.

4. Tool wear, which is particularly severe in conventional cutting of such materials as ESR 4340 steel and Refractaloy 26, was significantly reduced with ultrasonic activation.

5. Tool breakage occured less frequently with the ultrasonic assist, indicating reduced tool loading.

6. Ultrasonically cut chips showed a larger curl radius and a lower hardness, indicating lower chip strain as a consequence of lower tool/chip friction.

7. Chips from ultrasonic cutting showed less discoloration than conventionally cut chips, suggesting reduced heating effects.

8. Tool chatter, which frequently occured with heavy non-ultrasonic cuts, were instantaneously eliminated when the ultrasonic system was activated.

9. No consistent effect of ultrasonic activation on surface roughness was apparent under the conditions investigated.

10. The turret-type ultrasonic tool post, which for this investigation was installed on a LeBlond engine lathe, is practicable, with interface modifications, for installation on a turret lathe.

RECOMMENDATIONS

1. The ultrasonic equipment should be modified and refined for evaluation on a turret lathe in a production environment Such modifications should consist of:

   a. Redesign of the ultrasonic tool post to provide improved, positive tool retention.

   b. Installation of a power interlocking system to provide automatic activation of ultrasonic power when the cutting load is initiated.

   c. Development of feedback circuitry that will match the ultrasonic power delivery to the tool load in order to maximize impedance matching at the tool/work interface under varying machining conditions.

2. It is further recommended that a production turret lathe such as the Warner & Swasey Model 3A be equipped with the modified ultrasonic system for detailed evaluation of the effectiveness of ultrasonically assisted turning under production conditions.

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2. Maropis, N. and J. Devine, "Development and Evaluation of Ultrasonic I.D. (Boring) Single-Point Machining System." Research Report 72-7, Aeroprojects Inc., West Chester, PA, February 1972. (For Union Carbide Corporation, Nuclear Division, Oak Ridge, TN, under AEC subcontract)

3. Shaw, M. C., "Plastic Flow in the Cutting and Grinding of Materials." Proc. Nat. Acad. Sci., Vol. 40 (1954), p. 394-401.

4. Finne, I. and M. C. Shaw, "The Friction Process in Metal Cutting." Trans. ASME, Vol. 78 (August 1956), p. 1649-1657.

5. Meyer, F. R., "Engineering Feasibility Study of Ultrasonic Applications for Aircraft Manufacture." Research Report 73-15, Aeroprojects Inc., West Chester, PA, Army Contract DAAJ01-72-C-0737(P1G), September 1973.

6. Machining Data Handbook, Machinability Data Center, Metcut Research Associates Inc., Cincinnati, OH, Second Edition, 1972.

APPENDIX A

REPORTED INVESTIGATIONS ON ULTRASONIC TURNING OF METALS AND ALLOYS*

1. Voronin, A. A. and A. I. Markov, "Effect of Ultrasonic Vibrations on Machining of Heat-Resistant Alloys." Stanki i Instrument, 1960, No. 11, p. 15-17. (In Russian)

Ultrasonic radial activation of the cutting tool at 22 kHz during turning of heat-resistant steel alloys had variable effects, depending on the vibratory intensity. At high power levels (2-3.5 kw), tool life decreased, apparently because of significant increase in cutting temperature. At lower power (1 kw), tool life increased fourfold. The coefficient of chip contraction was also reduced, indicating reduced rate of plastic deformation in the shear layer. The ultrasonically cut surface had a mat finish, while that non-ultrasonically cut was bright and glossy.

2. Isaev, A.I. and V. S. Anokhin, "Ultrasonic Vibration of a Metal Cutting Tool." Stanki i Instrument, 1961, No. 5, p. 48-53. (In Russian)

An 8-kw, 18-kHz magnetostrictive transducer was used to vibrate a lathe tool in several directions, all in a plane normal to the lathe axis. Mild steel and nickel-chrome steel were turned at speeds up to 70 m/min, feeds up to 0.13 mm, and depths of cut up to 2 mm. With tangential vibration, surface roughness was reduced from 49-65 μ to 1-2 μ, edge build-up on the tool was eliminated, and workhardening of the material was reduced. All three components of cutting force were reduced, the effect becoming less pronounced as cutting speed was increased. Cutting temperature was higher with ultrasonic activation.

3. Kumabe, J., "Study of Ultrasonic Internal Grinding by Using the Longitudinally Vibrated Grinding Wheel, I." Japanese Society of Mechanical Engineers, Trans., Vol. 27, Sept. 1961, p. 1404-1411. (In Japanese)

The mechanism of ultrasonic cutting with a single-point cutting tool vibrating in the transverse direction was analyzed theoretically and experimentally. Cutting was carried out at a frequency of 20.3 kHz, vibratory amplitudes from 7 to 16.5 μ, depths of cut from 0.02 to 0.125 mm, and speeds up to 100 m/min.

*Data from Ref. 5.

Ultrasonic application significantly decreased required cutting forces, particularly at the lower speeds, and increased the cutting ratios. However, ultrasonic friction between tool and workpiece induced high temperatures at the tool edge and accelerated tool wear. It was suggested that a grinding wheel would perform more smoothly than a single-point cutting tool under ultrasonic influence.

4. Kumabe, J., "Study on Ultrasonic Cutting." Japanese Society of Mechanical Engineers, Trans., Vol. 27, Sept. 1961, p. 1389-1404. (In Japanese)

It was established that in ultrasonic metal cutting the direction of vibration should generally be in the direction of the cut. Principles and equations were developed for designing ultrasonic systems operating in the longitudinal and torsional modes, with both exponential and conical horns. The systems could be fixed statically or rotated. Lathe attachments were designed for operation at frequencies in the range of 10-40 kHz. A critical cutting speed, beyond which no further improvement with ultrasonic cutting was achieved, was found to be a function of frequency and amplitude.

5. Danielyan, A. M. and Yu. A. Gritsaenko, "Vibratory Cutting." Machines and Tooling (USSR), Vol. 33, June 1962, p. 51-52.

The status of ultrasonic machining of heat-resistant alloys was reviewed, and conflicting data were noted, indicative of a process in its first development stage. Further research was indicated to establish optimum frequency, power, vibratory direction, as well as ultrasonic effects on plastic deformation, tool wear, forces and temperatures, work-hardening, and surface finish.

6. Markov, A. I., Ultrasonic Machining of Intractable Materials. Mashgiz, Moscow, 1962. (English Translation by Scripta Technica Ltd., Iliffe Books Ltd., London, 1966)

On the basis of available information on ultrasonics applied during turning of heat-resistant alloys, the author concluded that practical application of the process was held back by the complexity, inadequate strength, and high cost of existing ultrasonic equipment. The necessity for providing a rigid system in order to obtain maximum results was emphasized.

7. McKaig, H.L., "Applications of Ultrasonics to Metal Forming and Rolling." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963, p. 33-36.

Ultrasonic activation of a lathe tool during turning of 2024 aluminum alloy, 4340 steel, and unalloyed titanium resulted in up

to 30% reduction in cutting force, elimination of tool chatter, and altered surface finish. It was suggested that fatigue strength may be improved by ultrasonic turning.

8. Skelton, R. C. and S. A. Tobias, "A Survey of Research on Cutting with Oscillating Tools." Advances in Machine Tool Design and Research, S. A. Tobias and K. K. Koeninsberger, Eds., Macmillan Co., New York, 1963, p. 5-16. Also "Putting Vibrations to Work," Metalworking Production, Vol. 106, Oct. 24, 1962, p. 65-68.

Review of available literature (primarily Russian) on controlled vibration of a lathe tool indicated effects such as improved chip breaking, reduction in cutting forces, increase in tool life, decrease in cutting temperature, elimination of edge build-up on tool, reduction in workhardening, and increase in cutting fluid effectiveness. The magnitude of the effects was reported to depend upon the vibratory amplitude, frequency, and direction of cut, its phase relation to the previous cut, and the normal cutting parameters of feed, speed, depth of cut, etc. Vibration was usually in the direction of feed, since surface finish was otherwise adversely affected. Frequencies ranged from a few hertz to over 20 kHz.

9. Nerubay, M. S., "Investigation of the Effectiveness of Ultrasonic Vibration of the Tool When Machining Heat-Resistant and Titanium Alloys." Kuybyshev Aviatsionnye Institut, Trudy, USSR, 1963, No. 18, p. 15-27. (Air Force Translation FTD-MT-24-162-70)

Several difficult-to-machine alloys were turned on a lathe under the influence of vibration at 18-25 kHz in a radial mode. The chips showed reduced longitudinal shrinkage, edge build-up on the tool was minimized, and the quality of the cut surface was improved. At low amplitudes, temperature in the cutting zone decreased and cutting force decreased. At high amplitudes, temperatures and forces increased, and there was greater work-hardening in the cut layer.

10. Balamuth, L., "Recent Developments in Ultrasonic Metalworking Processes." SAE Paper 849G, Air Transport and Space Meeting, New York, April 27-30, 1964. Also Balamuth, "Ultrasonic Metalworking." American Machinist, Vol. 108, April 13, 1964, p. 136-138.

Preliminary experiments in single-point cutting on an aluminum block with a lathe tool mounted on a surface grinder resulted in considerable chatter in making a 0.060-inch-deep cut. With 20 kHz vibration of the tool, tool forces were reduced, chatter marks completely disappeared, and the cut was smooth.

11. Aeroprojects Inc., "Investigation of Vibratory Excitation of Cutting Tool During Lathe Turning." Research Report 64-76, West Chester, PA, Sept. 1964.

Experiments were carried out in turning several steel alloys, including 4340 and Vasco-Jet 1000, with 20 kHz ultrasonic excitation of the cutting tool in a direction tangential to the surface being cut. Tool force reductions ranged up to 60%; the effect decreased with increasing cutting speed, feed and depth of cut, suggesting that higher power should be used at the greater metal removal rates. At the higher cutting speeds, tool life was increased. The work established the practicability of installing an ultrasonic system on a standard lathe with minimum modification.

12. Kristoffy, I. I., R. L. Kegg, and R. R. Weber, "Influence of Vibrational Energy on Metalworking Processes." Report AFML-TR-65-211, Cincinnati Milling and Grinding Machines, Inc., Cincinnati, Ohio, Air Force Contract AF 33(657)-10821, July 1965.

Ultrasonic vibration of the cutting tool at 24 kHz in the tangential direction effected force reductions up to 90% in turning (and facing) of aluminum alloy, copper, steel, and brass. The effect was reduced at increased feeds and cutting speeds but was increased with increasing vibratory amplitude. In addition, chatter was inhibited, and surface finish and chip formation were improved.

13. "Ultrasonic Energy Aids Turning, Grinding, Machining." Steel, Vol. 157, July 12, 1965, p. 58-60.

Ultrasonic application to lathe turning was said to be technically feasible because of such demonstrated benefits as 10-50% tool force reduction (depending on power input), improved surface finish, especially with aluminum and titanium alloys, and elimination of tool chatter. Recent developments in ultrasonic equipment design appeared to offer sufficient refinements for field evaluation of the process by industry.

14. Dohmen, H. G., "Machining Research with Ultrasonically Excited Turning Tools." Industrie-Anzeiger, Vol. 88, Jan. 26, 1966, p. 115-122. (In German)

In turning aluminum and steel cylinders with 20 kHz ultrasonically activated tools, surface finish was significantly improved at the lower cutting speeds, smoother, more continuous chips were obtained, and edge build-up was completely eliminated. Surface finish was improved only when the direction of vibration coincided with the direction of the principal cutting force, not in the transverse direction. Several hypotheses for explanation of the effects were presented. Successful ultrasonic application to other chip-making processes, such as broaching and reaming, was postulated.

15. Bayles, W. H., "Ultrasonic Machining of Hard Ceramics: An Engineering Evaluation." Research Report 68-63, Aeroprojects Inc., West Chester, PA, Oct. 1968.

Ultrasonic single-point machining of hard ceramics was demonstrated by means of linear unidirectional cuts with a diamond tool on an alumina composition. Ultrasonic tool activation in a direction longitudinal, vertical, or transverse to the direction of cut reduced tool forces by as much as 80% and produced wider and deeper cuts, indicating increased rate of metal removal. Tool chatter was effectively eliminated. Ultrasonic power requirements were low, approximately 25 electrical watts input to a magnetostrictive transducer. Requirements for an ultrasonic machining array for installation on a standard metalworking lathe were evolved.

16. Maropis, N. and J. Devine, "Development and Evaluation of Ultrasonic I.D. (Boring) Single-Point Machining System." Research Report 72-7, Aeroprojects Inc., West Chester, PA, Feb. 1972.

An experimental ultrasonic boring system was developed utilizing a 28 kHz axial/torsional mode conversion transducer-coupling array delivering up to 450 acoustical watts power to interchangeable cutting tools. Evaluation in machining 2024-T6 aluminum alloy and 1018 HR steel showed substantial tool force reduction (21-71% depending on material, machining rate, and tool type). Machined surfaces were smoother than with non-ultrasonic cuts, subsurface material disturbance was markedly reduced, and chips had smoother edges and greater curl radius. The equipment was installed on a lathe in an AEC plant for further evaluation.

17. Devine, J. and W. B. Tarpley, "Ultrasonic Machining." Presented at 83rd Annual Meeting of the Acoustical Society of America, Buffalo, NY, April 18-21, 1972. Also J. Devine, "Ultrasonically Assisted Metal Removal," SAMPE Quarterly, Vol. 10 (April 1979).

Ultrasonic application to single-point metal cutting, as in turning, drilling, and boring was reviewed. Stated benefits in these processes were increased material removal rates, reduced tool loads, improved surface finish, reduced subsurface deformation, favorable chip alterations, elimination of tool edge buildup, and extended tool life. The ultrasonic assist was noted to offer increased productivity, solution of recalcitrant metal removal problems, and production of superior machined items.

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Technical Report AVRADCOM TR 80-F-18 (AMMRC TR 80-50), October 1980, illus-tables, Contract DAAG46-78-C-0059, D/A Project 176156, AMCMS Code 1497.94.6.S7156 (XR6), Final Report, August 1978 - March 1980

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A tool post for ultrasonic activation of cutting tools on a turret lathe was designed, fabricated, and given preliminary evaluation on a LeBlond engine lathe in turning difficult-to-machine wrought metal alloys, including ESR 4340 steel, 4340 steel, 9310 steel, 17-4 PH steel, several titanium alloys, and Refractaloy 26. With the ultrasonic assist, metal removal rates were increased by factors up to 730 percent, tool wear and tool breakage were reduced, and tool chatter was eliminated. Ultrasonically cut chips had larger curl radius, lower hardness, and less heat discoloration than conventionally cut chips. It was recommended that the ultrasonic tool post be refined and installed on a turret lathe for evaluation in a production environment.

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